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NUCLEAR CRATERING EXPERIENCE AT THE PACIFIC PROVING GROUNDS

Livermore, California

UCRL-12172
TID-4500, UC-35,
Nuclear Explosions-Peaceful Applications

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Livermore, California

Contract No. W-7405-eng-48

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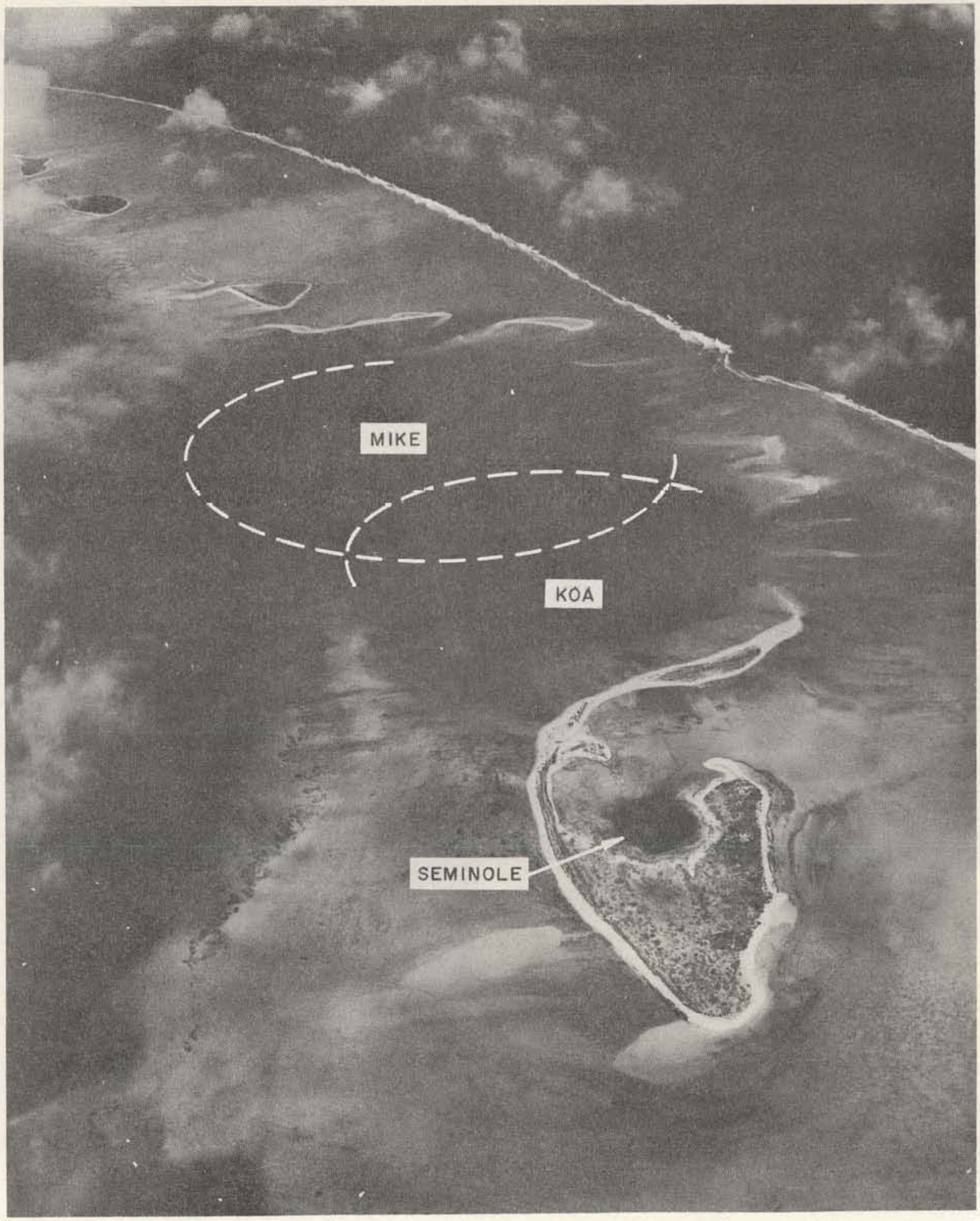
Louis J. Circeo, Jr.
Milo D. Nordyke

November 10, 1964

Printed in USA. Price $2.00. Available from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U. S. Department of Commerce, Springfield, Virginia



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NUCLEAR CRATERING EXPERIENCE AT THE PACIFIC PROVING GROUNDS

Louis J. Circero, Jr. and Milo D. Nordyke

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ABSTRACT

This study was conducted to observe the long-term effects of weathering on 10 nuclear craters over periods as long as 12 years. The study consisted of an investigation and resurvey of selected craters on Bikini and Eniwetok Atolls, including documentary photography; hydrographic, topographic, and geologic data; and general engineering observations. These data were compared with information collected from previous pertinent reports and studies.

This report summarizes all the data from previous and present studies. Cratering curves for these surface detonations are developed, based primarily on the empirical data. Crater radius is shown to scale as $W^{1/2.5}$, similarly to the observed scaling dependence of other fireball phenomena. Crater depth after water washing was shown to scale as $W^{1/4}$. The effect of low heights of burst appears to be relatively minor in determining crater dimensions. Changes in crater topography are noted and investigated. The alteration of shoreline processes as a result of nuclear craters is discussed. The comparison of craters formed by surface and subsurface detonations and subsequent phenomena is considered.

It is suggested that this study form the basis for further investigations of the craters in the Pacific Proving Grounds. Future studies will provide additional information of the condition and changes occurring in the craters and the surrounding area.

INTRODUCTION

Purpose of Study

The use of nuclear explosives to make large-scale excavations is one of the principle areas of study of the Plowshare Program. The potential uses of nuclear excavation include such applications as highway and railroad cuts, harbors, canals, and other water-conveyance systems. These applications raise many questions which are under study by Plowshare, including those related to engineering feasibility as well as the immediate cratering effects of the nuclear detonation.

At the present time, much engineering research is being conducted on nuclear craters at the Nevada Test Site. However, many potential applications include the introduction of water into the excavation site both during excavation process and after the completed excavation. Thus it becomes necessary to evaluate the effect of water on

1. Cratering parameters;
2. Crater lips and slopes, when water-washed;
3. Short- and long-term slope stability; and
4. Silting-up of an excavation.

In order to gain a better understanding of these phenomena, a recent study was undertaken at a number of craters produced by nuclear explosions at the Pacific Proving Grounds. During the period from 1952 to 1958, 61 detonations with yields ranging from the kiloton range up to 15 megatons were conducted.[1] Many of these explosions resulted in the formation of craters. All of the detonations were essentially surface bursts and almost all were water-washed. Several were destroyed by subsequent explosions with the result that only partial data exist.

Application of Data to Plowshare Studies

In spite of the above limitations, many interesting and valuable data can be obtained from these craters. Results from 10 of these detonations which produced good craters are reported here. Comparison of these data with results of nuclear and chemical explosive craters at the Nevada Test Site leads to some interesting conclusions regarding the effects of water on large-scale nuclear craters.

The present study affords the opportunity to observe the long-term changes of nuclear craters over periods as long as 12 years. Therefore, along with the immediate considerations of cratering parameters and water-washing, it is possible to investigate such problems as the effect of craters on the natural environment of the area, the effect of sustained wave action on the craters, and the results of long-term inundation on slope stability and erosion.

It is unfortunate that this study must be compared with previous data which were taken without the objectives of this investigation in mind, since measurements of a more detailed and pertinent nature could have been taken. Also, the destruction of some craters by subsequent detonations eliminated the observation of changes which would have taken place in them over the years. However, the existing data are sufficient to allow a meaningful study. Future studies will have the advantage of using the present investigation to study later and more detailed effects of water on nuclear craters.

BACKGROUND

Site Location

The Pacific Proving Grounds consists of two coral atolls, Bikini and Eniwetok Atolls, which are located in the Marshall Island Group in the Pacific Ocean at approximately 12° N latitude, 165° E longitude (Fig. 1). The Northern Marshalls have a tropical oceanic climate characterized by uniform temperature and high humidity. The mean annual temperature is 82° F; the relative humidity averages 82%. Eniwetok Atoll receives about 50 inches of rain per year.

Bikini is an atoll in the Ralik chain of the Marshall Islands, about 225 miles NW of Kwajalein Island. The atoll is a coral ring of more than 20 islands, with a lagoon about 25 miles long (Fig. 2). Eniwetok Atoll is located approximately 200 miles west of Bikini. Its annular reef supports some 30-odd low islands and encloses a shallow, elliptical lagoon, about 20 miles wide and 25 miles long (Fig. 3).

Geology

The geology of atolls has been described in the following summary of Eniwetok Atoll[2]:

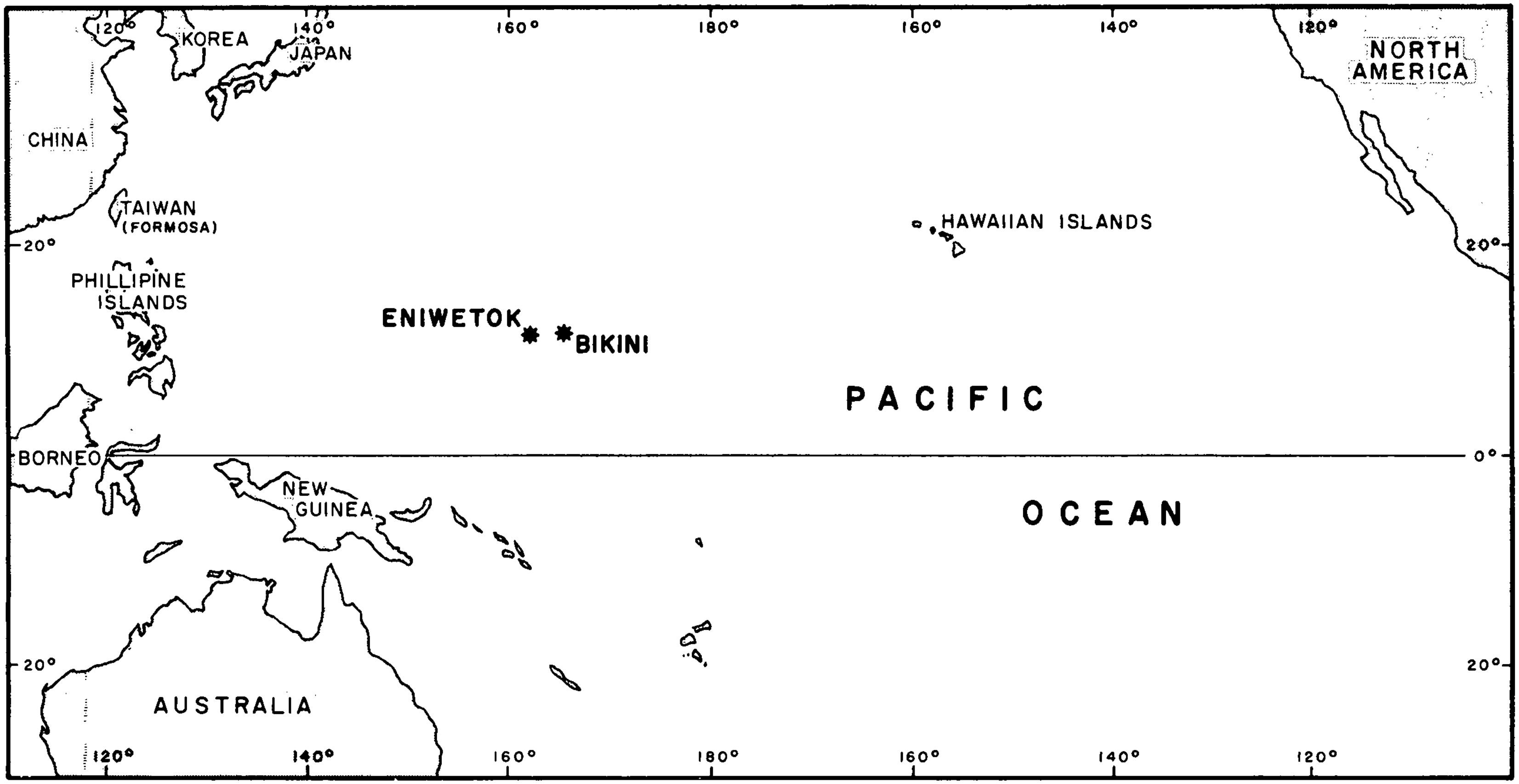

Fig. 1. Location of Eniwetok and Bikini Atolls.

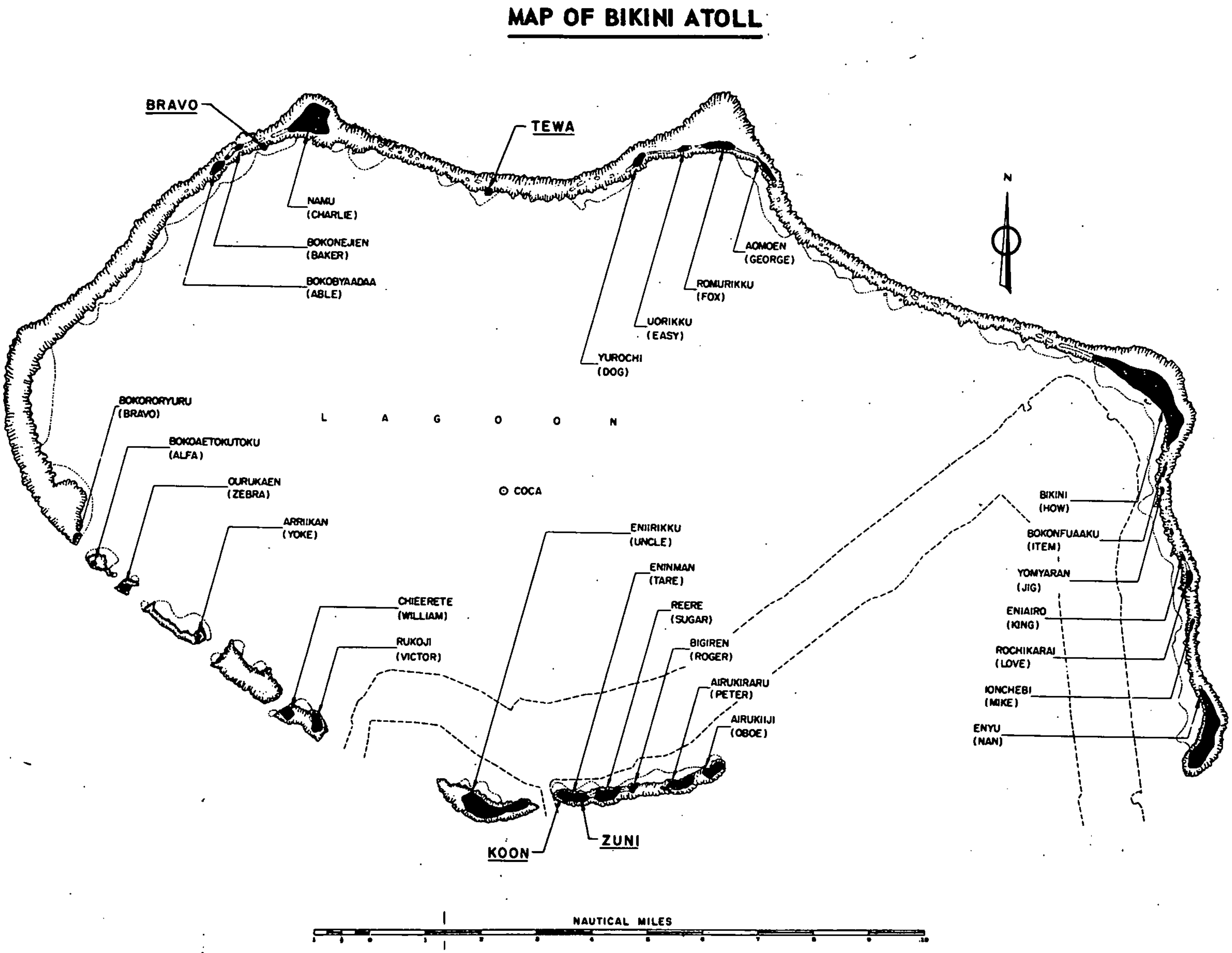

Fig. 2. Map of Bikini Atoll, showing the location of the four craters under investigation.

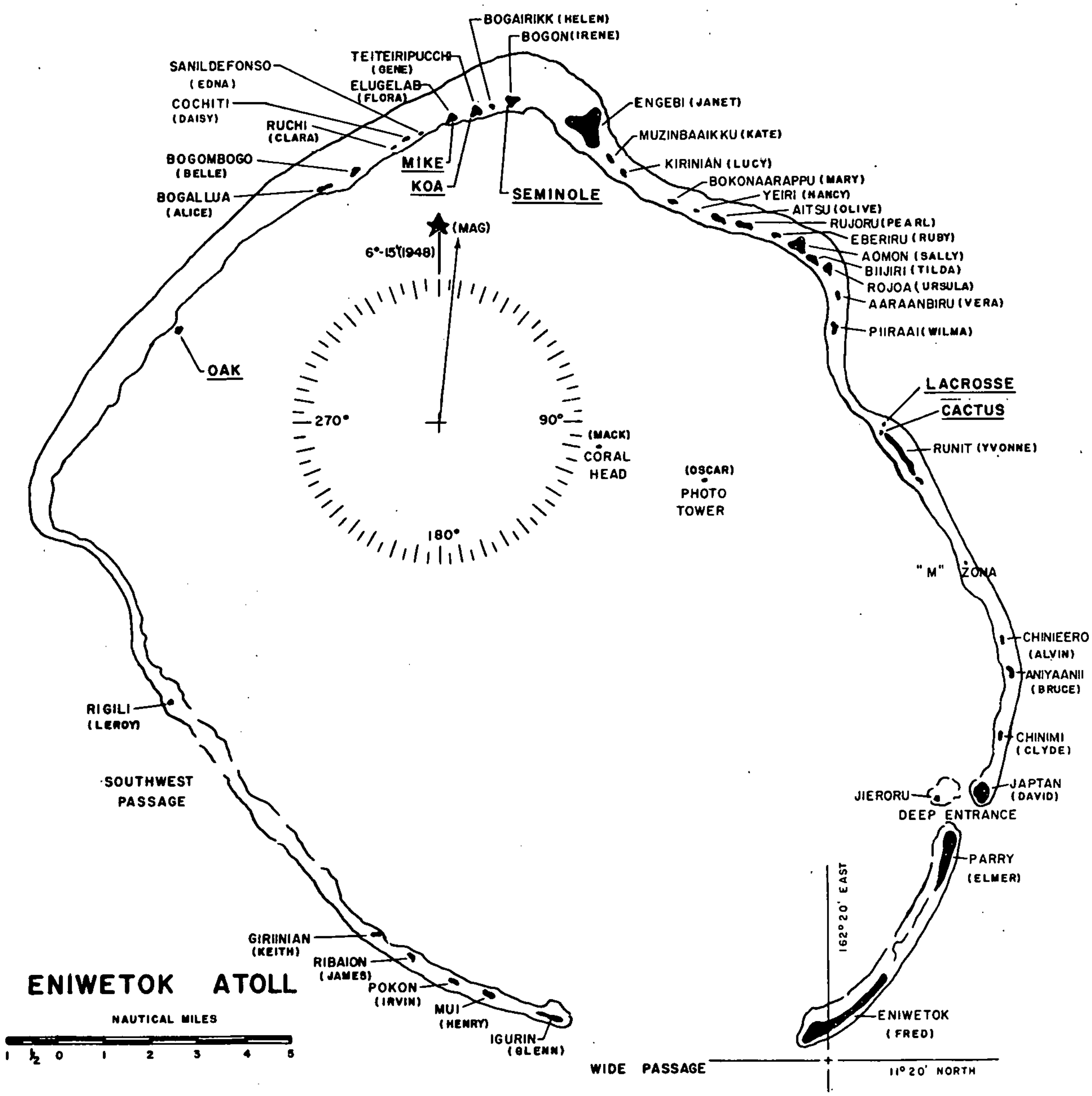

Fig. 3. Map of Eniwetok Atoll, showing the location of the six craters under investigation.

> The atoll consists of various layers of lenses of material interspersed with large cavities of water and air. With the exception of a few feet of hard rock at a depth of approximately 20 feet, the atoll is composed primarily of soft, unconsolidated sedimentary beds contained on the ocean side by a sheath of coral rock of varying thickness. This container wall is expected to have numerous weak spots because of joints and fissures characteristic of coral formations. At depths greater than 1100 feet, hard or firm sedimentary layers become more prevalent and at a depth of 2900, running up to 1000 feet in thickness, the atoll is made up of a soft, chalky limestone. The atoll rests on a consolidated basalt floor, which is about 4000 feet below sea level.

This information was derived from two boreholes over 4000 ft deep with supplementary information from several shallow borings on Bikini and Eniwetok, from dredging on the seaward atoll slopes at great depth, and from various geophysical surveys. Drilling logs of holes in the islands of Yvonne, Helen and Irene, Eniwetok Atoll are given in Tables I, II and III.[3]

Table I. Shot Cactus drilling log, Yvonne, station 181.03.[3] Coordinates: N 105,618.17: E 124,611.56.

Depth (ft)	Description
1 to 8	Soft sand
8 to 16	Hard cemented sand
16 to 23	Soft cemented coarse sand with hard layers
23 to 32	Soft cemented sands with shells
32 to 45	Soft cemented sands with shells and hard layers
45 to 50	Hard cemented sands with shells
50 to 58	Hard cemented sands with shells
58 to 62	Soft cemented sands with hard layers
62 to 72	Soft cemented sands and shells
72 to 108	Soft cemented sands and shells with hard layers

Table II. Helen drilling log, station 180.02.[3] Coordinates: N 149,507.11: E 74,247.25.

Depth (ft)	Description
1 to 10	Full sand
10 to 15	Hard coral
15 to 20	Hard coral with black coral
20 to 25	Cemented rubble with black coral
25 to 35	Hard coral with black coral
35 to 40	Cemented rubble
40 to 50	Cemented rubble with shells
50 to 90	Cemented sand with rubble
90 to 108	Cemented rubble with shells

Table III. Irene drilling log, station 180.03.[3] Coordinates: N 150,329.74: E 74,949.11.

Depth (ft)	Description
1 to 10	Soft powdered sand to soft sand
10 to 20	Soft sand and shells
20 to 40	Soft rubble and sand
40 to 60	Cemented rubble
60 to 80	Cemented rubble and sand
80 to 108	Cemented sand and shells

Crater Surveys

Previous Studies

The results of the ten detonations of interest are summarized in Table IV, where the detonation and crater parameters are shown. Burst heights signify the height of detonation above the original ground surface, except as noted. The locations of the various events are shown in Figs. 2 and 3.

Information from previous studies relating to the present investigation was obtained from a variety of sources which are listed as references at the end of this report. Additional information was obtained from many of the agencies originating these documents. In addition to the detonation parameters of each

Table IV. Summary of cratering data at Pacific Proving Grounds.

Shot series and name	Shot date	Time (GCT)	Location	Yield (kt)	Burst height[a] (ft)	Crater radius (ft)	Original crater depth (ft)	1964 crater depth (ft)
Ivy								
Mike	10/31/52	1915	Eniwetok	10,400	35	2800	164	87
Castle								
Bravo	2/28/54	1845	Bikini	15,000	15.5	3000	240	
Koon	4/6/54	1820	Bikini	110	13.6	400	40	
Redwing								
Lacrosse	5/4/56	1825	Eniwetok	39.5	17	202	44	41
Zuni	5/27/56	1756	Bikini	3,530	9	1240	115	
Seminole[b]	6/6/56	0055	Eniwetok	13.5	4.5	255-390	31	22
Tewa	7/20/56	1748	Bikini	5,010	20[c]	2000	129	
Hardtack								
Cactus	5/5/58	1815	Eniwetok	18	3	185	36	33
Koa[a]	5/12/58	1830	Eniwetok	1,370	3	1825	135	105
Oak	6/28/58	1930	Eniwetok	8,900	6.5[d]	2200	183	

[a]Distance above the original ground surface, except as noted.

[b]Detonated in a tank of water.

[c]Detonated on a barge in 20 feet of water. Height of burst above water not known.

[d]Detonated on a barge 6.5 feet above the water surface. Water was 13 feet deep.

shot, the most pertinent information related to this study were the postshot crater shapes and dimensions and the photographs of the craters from which comparisons may be made.

Preshot contours of the areas were made to the extent possible in each shot. Land areas were surveyed by standard surveying techniques. Water-covered areas were more difficult to survey and the results were generally not as satisfactory. Soundings were made with standard recording echo fathometers, and positions were estimated by such methods as fixes on shore locations or by Raydist equipment. In addition, preshot photos of all shot areas were made for comparison with postshot photos. Since the surveys were taken under varying tide heights, it was necessary to reduce all depth readings to a common datum plane of 0.5 ft below mean low-water spring.

Postshot surveys were made by a variety of methods. When conditions allowed, fathometer equipment was used; for some craters, where radiation levels did not permit surface work, helicopters were used. In general, postshot work included only a few soundings at the center of the crater and along one or two radii. As the data were obtained from several sources, minor inconsistences in the results of previous studies will be noted in this report.

Present Studies

In order to examine the effects of water on long-term crater changes, an investigation of the craters on Eniwetok Atoll was conducted in April, 1964. This study consisted of the following phases:

Resurvey of craters. All of the Eniwetok craters, except Oak, were resurveyed using, as near as possible, the same rays and range line sounding stations and techniques used on previous surveys. This duplication of survey was required to compare the current configuration of each crater with the former postshot appearance. The shot points, survey control stations, and land-based ray points of all craters were marked and recorded for aerial photography and future investigation purposes. Range lines were extended out to significant distances to include the lip zones where applicable. The surveying was done by Holmes and Narver, Inc.

Documentary photography. Documentary photography was done by the Graphic Arts Department, Lawrence Radiation Laboratory. This photography included aerial stereo photography, aerial color photographs, and ground color and black-and-white photography.

Arrangements were made with Bendix Corporation, Pacific Missile Range Downrange Facility, to utilize their aerial mapping camera to obtain aerial photographs of all craters. These photographs were valuable for all phases of the crater investigation, including comparison with previous photographs, the study of wave action and erosion, and photogrammetric mapping of the craters.

Hydrographic, topographic, and geologic data. Hydrographic information for the crater surveys was obtained from "PMR Project, Eniwetok Atoll, Tide Tables." Local current investigation in the craters could not be conducted in a manner that would provide significant results in the time scale of this project. However, visual and photographic observations were made and are reported.

Sand build-up and erosion in and around the craters was evaluated through aerial photographs. Personnel from the U. S. Army Engineer Waterways Experiment Station (WES) mapped and investigated the effects of upheaval and ejecta around the visible crater lips. In addition, the engineering characteristics of these craters relating to erosion and stability were studied. These investigations were primarily concerned with the Cactus and Lacrosse craters. Representative soil samples were obtained around selected craters by WES personnel for density determinations, classification tests, and mapping of the crater lips. The results of these investigations will be published by WES in a separate report.[4]

Topographic maps of the Lacrosse, Cactus and Seminole craters were made from the aerial stereophotos, using the surveys as reference points. It was possible to map the craters to depths several feet below the water line. Below these points the lead-line surveys were used to map the remaining portions of these craters.

INVESTIGATION

Crater and Shot Histories

The following is a brief summary of each event, giving the conditions surrounding the shot and its emplacement, and the problems encountered in the measurement of the crater dimensions.

Mike

Mike was a 10.4-Mt detonation on the island of Flora, Eniwetok Atoll. The height above the island to the center of the device was 35 ft. Preshot and postshot photographs of the area are shown in Figs. 4 and 5.[5] The crater was measured by standard survey procedures and by soundings taken about 2 weeks after the shot showing the crater and the extent of openings to the lagoon. Figure 6 is a contour map of the immediate crater area showing the

Fig. 4. Preshot Mike area.[5]

Fig. 5. Postshot Mike area, showing preshot Koa ground zero location.[5]

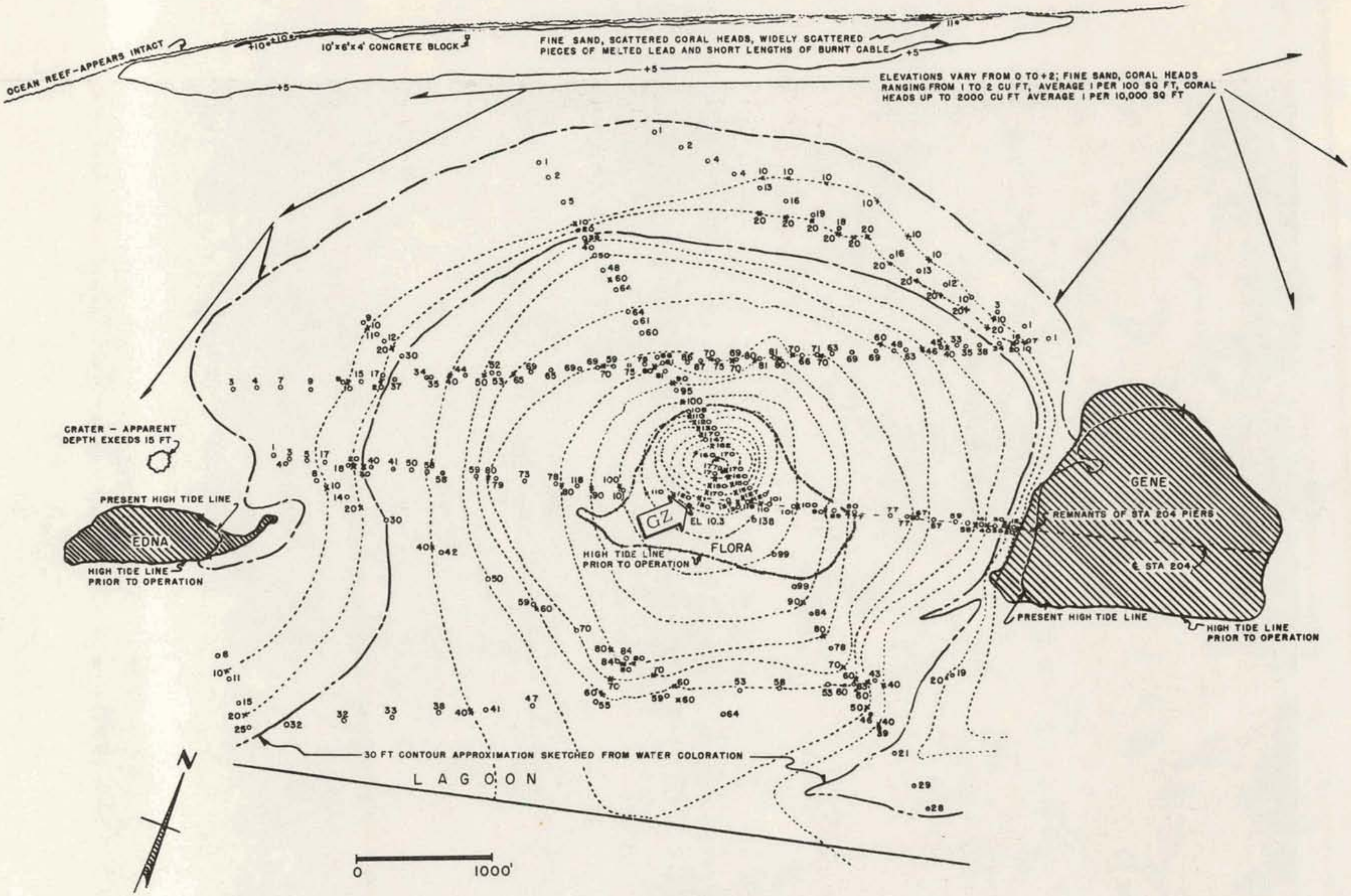

Fig. 6. Postshot contour map of Mike crater.[6]

sounding along various rays in the crater.[6] Note the deepest point in the crater was displaced approximately 300 ft northeast of the detonation point. The entrance channel from the lagoon into the crater was about 35 ft deep.

The 1964 survey was made by fathometer, with lead-line soundings to verify fathometer readings. The results of the post-event and 1964 surveys are shown in Fig. 7. One of the 1964 survey lines goes from the Mike zero point through the zero point of the adjacent Koa crater, which is discussed in a later section. The survey lines for both Mike and Koa craters are shown in Fig. 8. The greatest change in the Mike crater shape is a silting-up of the bottom. This has been caused mainly by settling of mud and silt in suspension, and throwout from the adjacent Koa shot (see frontispiece).

Bravo

Bravo was a 15-Mt detonation on the end of a long split extending out into the reef area west of Charlie Island, Bikini Atoll. The device was detonated 15.5 ft above the original ground surface. Postshot survey with a sonic fathometer 6 days after the shot showed a flat bottom at 170 ft which probably represented the upper surface of mud and suspended sand which had fallen or washed back in the crater and was settling to the bottom. Lead-line soundings several weeks later gave depths of 240 ft, which is believed to be the actual depth of the crater. The crater had a radius of about 3000 ft. Figures 9 and 10 show preshot and postshot aerial photomosaics of the area.[7]

Koon

Koon was a 110-kt shot on the west end of Tare Island, Bikini Atoll. The surface elevation at ground zero was 12 ft above sea level and the device was 13.6 ft above the ground surface. Figure 11 is a preshot photo of the island with the device located in the building in the lower left corner as indicated. Figures 12 and 13 are postshot photos taken the day of the shot.[7,8] It is obvious in the latter photo that there was no appreciable lip produced although there were hummocks 20-30 ft high. Unfortunately, postshot surveys were not taken until 24 days after the shot, and the wave from another shot (Union) on the other side of the atoll had washed over the crater.

These surveys, made with fathometer and lead-line soundings, showed a very flat-bottomed crater 40 ft deep, measured from the original ground surface, with a water depth of about 28 ft in the crater. The entrance channel

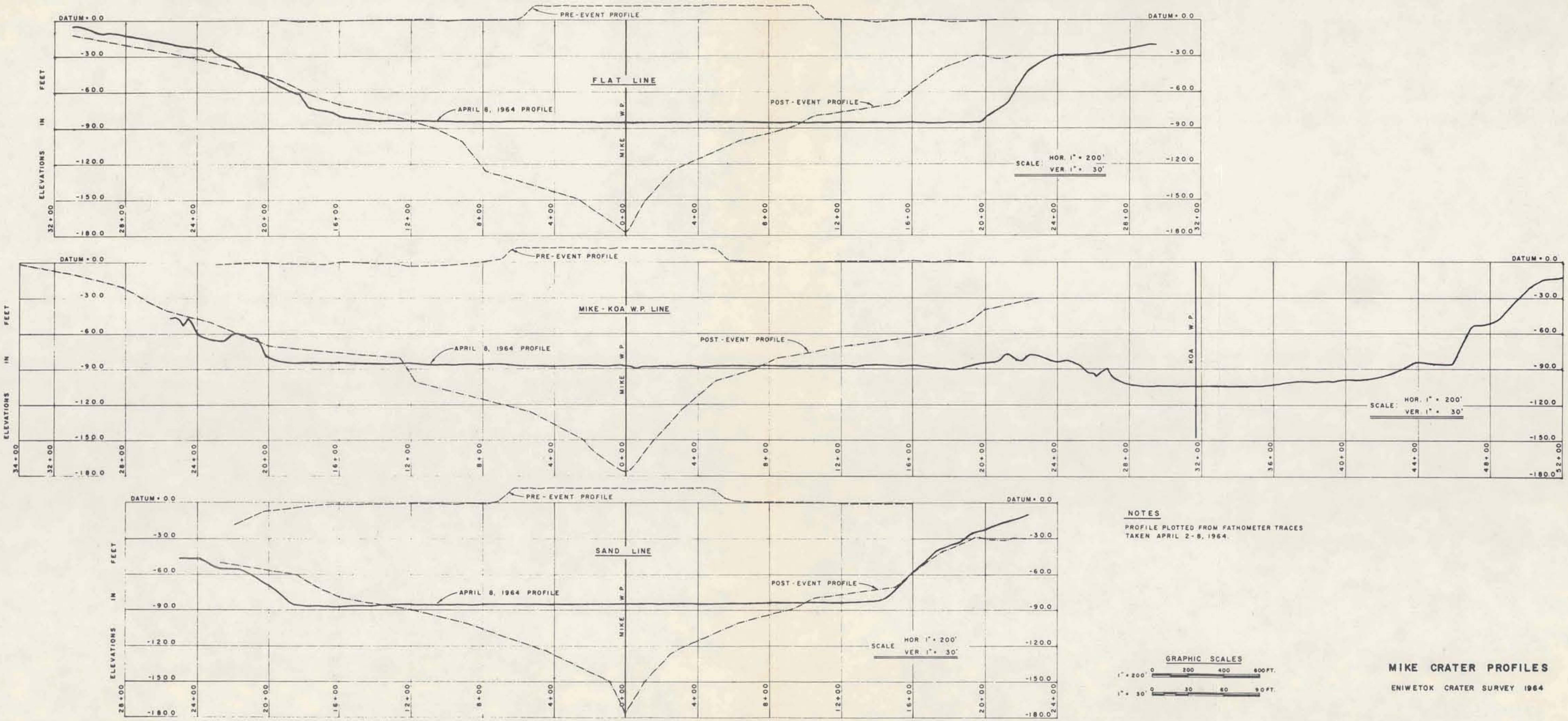

Fig. 7. Preshot, postshot, and 1964 survey profiles of Mike crater. Note the profile through the Mike and Koa zero points.

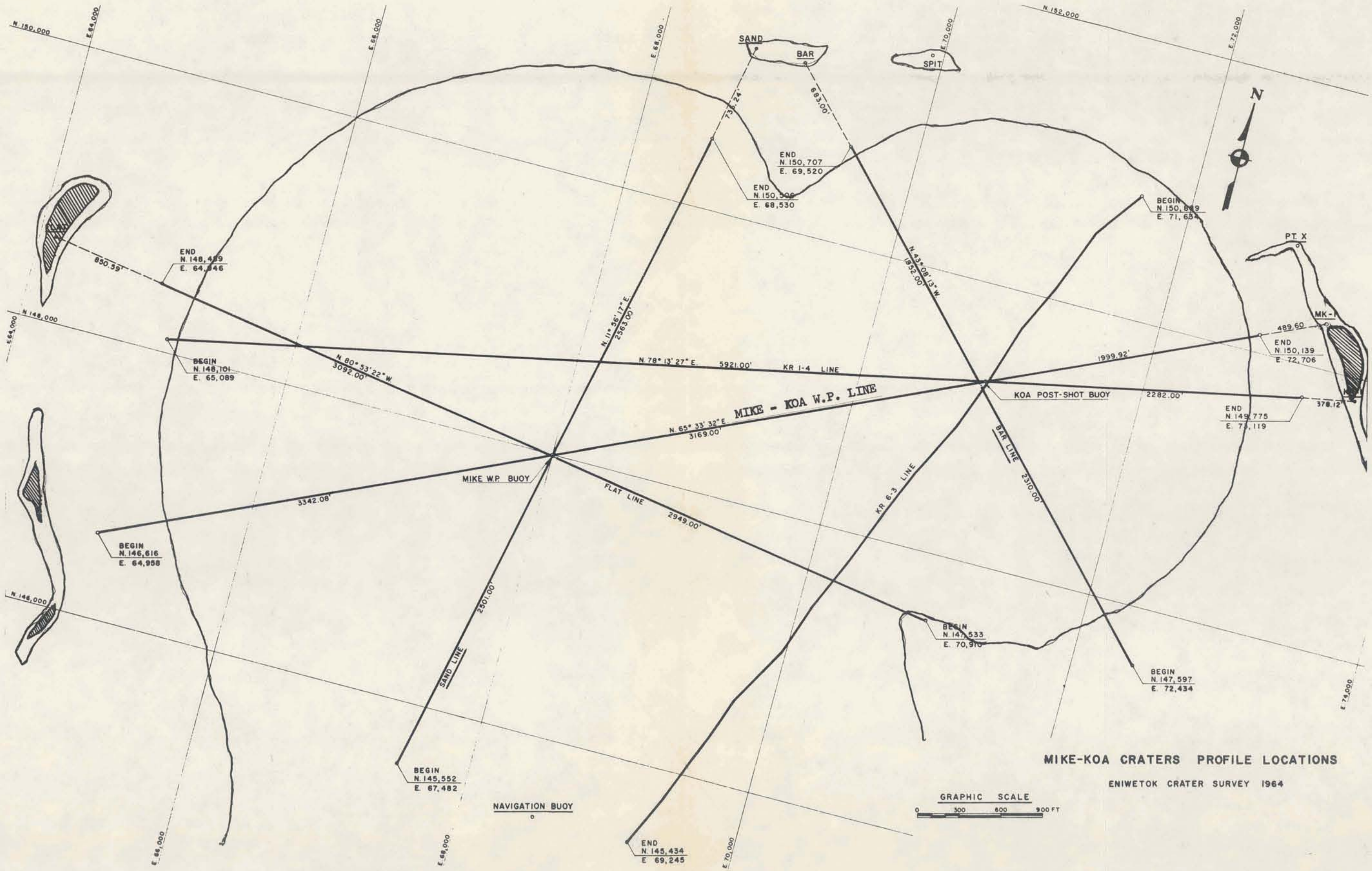

Fig. 8. Mike-Koa craters profile locations.

Fig. 9. Preshot Bravo area.[7]

Fig. 10. Postshot Bravo area.[7]

Fig. 11. Preshot Koon area.[7]

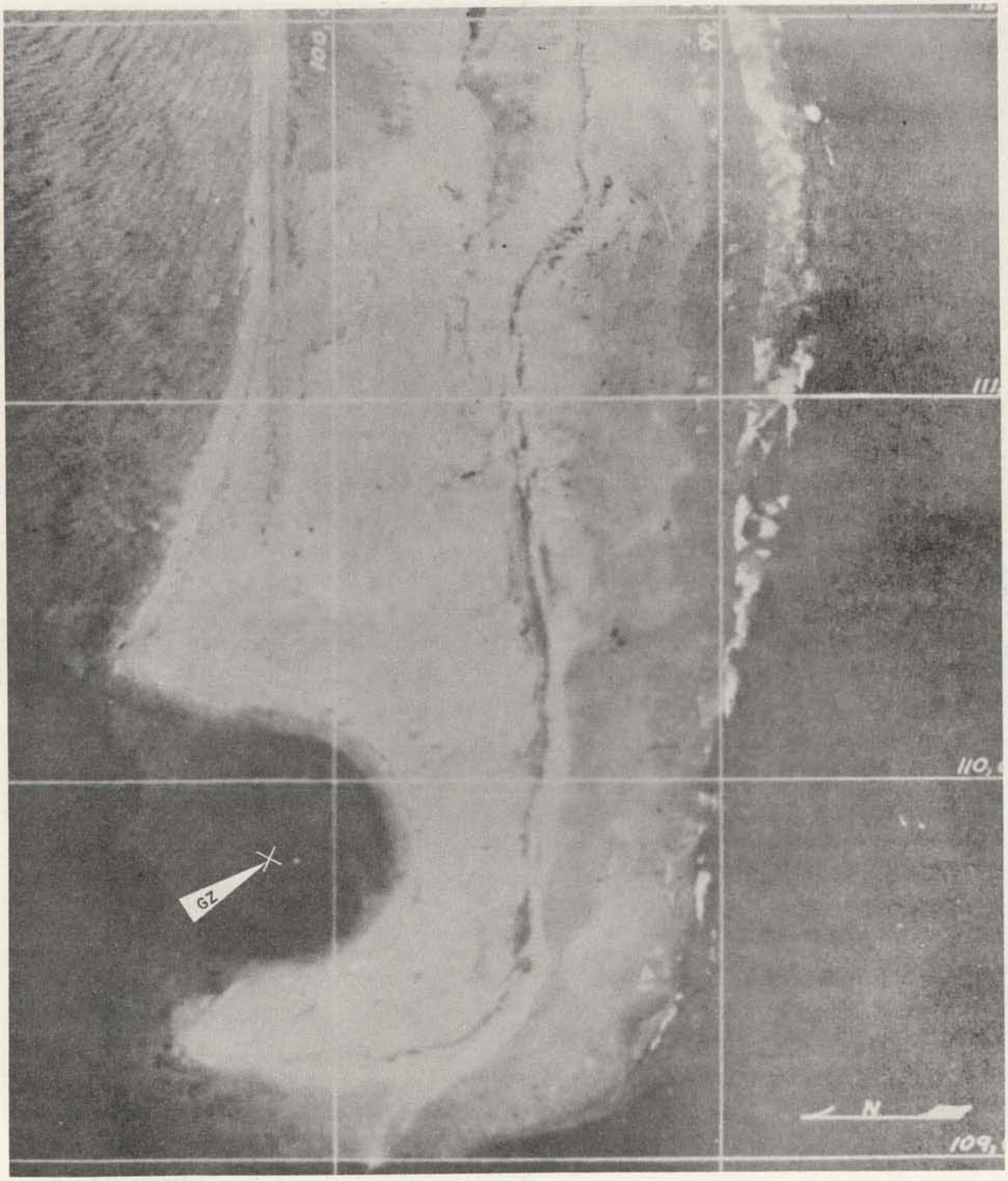

Fig. 12. Postshot Koon area taken the day after the event.[7]

Fig. 13. Koon crater taken the day after the event.[7]

into the lagoon was about 6 ft deep. The slope of the above-water lip from original ground level down to sea level varies over a wide range. To the south it was quite steep and the radius in that direction ranges from 380 to 410 ft. To the east and west, however, the slope is extremely gentle and the radius figure is uncertain and of little significance.

Undoubtedly, the flat-bottomed nature is due to filling in by the wave that broke over the island from the later shot. Thus, the crater depth would be smaller than expected. Figure 14 is an aerial photo taken two years later, and the change in shape of the crater is very apparent. The action of the waves has noticeably eroded away the sides of the entrance channel, but the shape of the deep crater is still very much in evidence.

Lacrosse

Lacrosse was a 39.5-kt device which was detonated on an earthfill causeway built on the reef off the end of the island of Yvonne, Eniwetok Atoll (Fig. 15). The center of the device was located 8.5 ft above the causeway which was in turn built 8.5 ft above the datum plane, which was very close to the original ground surface. The resulting crater had a radius of 202 ft and a depth of 44 ft. Figures 16 and 17 are postshot photographs of the detonation.[9] Figure 18 shows the results of stereophotogrammetric measurements of the Lacrosse crater. This shows that the lip of the crater was about 2.5-10 ft above the datum plane. The Lacrosse crater was not water-washed by returning water as were most other craters reported here, due to the shallow depth of water on the reef. Note that the water level in the crater immediately after the shot is 20 ft below the surrounding water level on the reef.

Figure 19 shows the postshot and 1964 results of lead-line soundings surveys made by a boat traversing the crater. Since the crater appeared symmetric, only range lines 1 and 4 were surveyed after the shot.[2] The 1964 survey shows that a small amount of erosion has taken place on the slopes of the crater, and has filled the bottom of the crater to a maximum depth of about 5 ft. Figure 20 is a photograph of the crater taken during the 1964 survey. Figure 21 is a contour map of the crater made from stereophotogrammetric measurements and the lead-line surveys made in 1964.

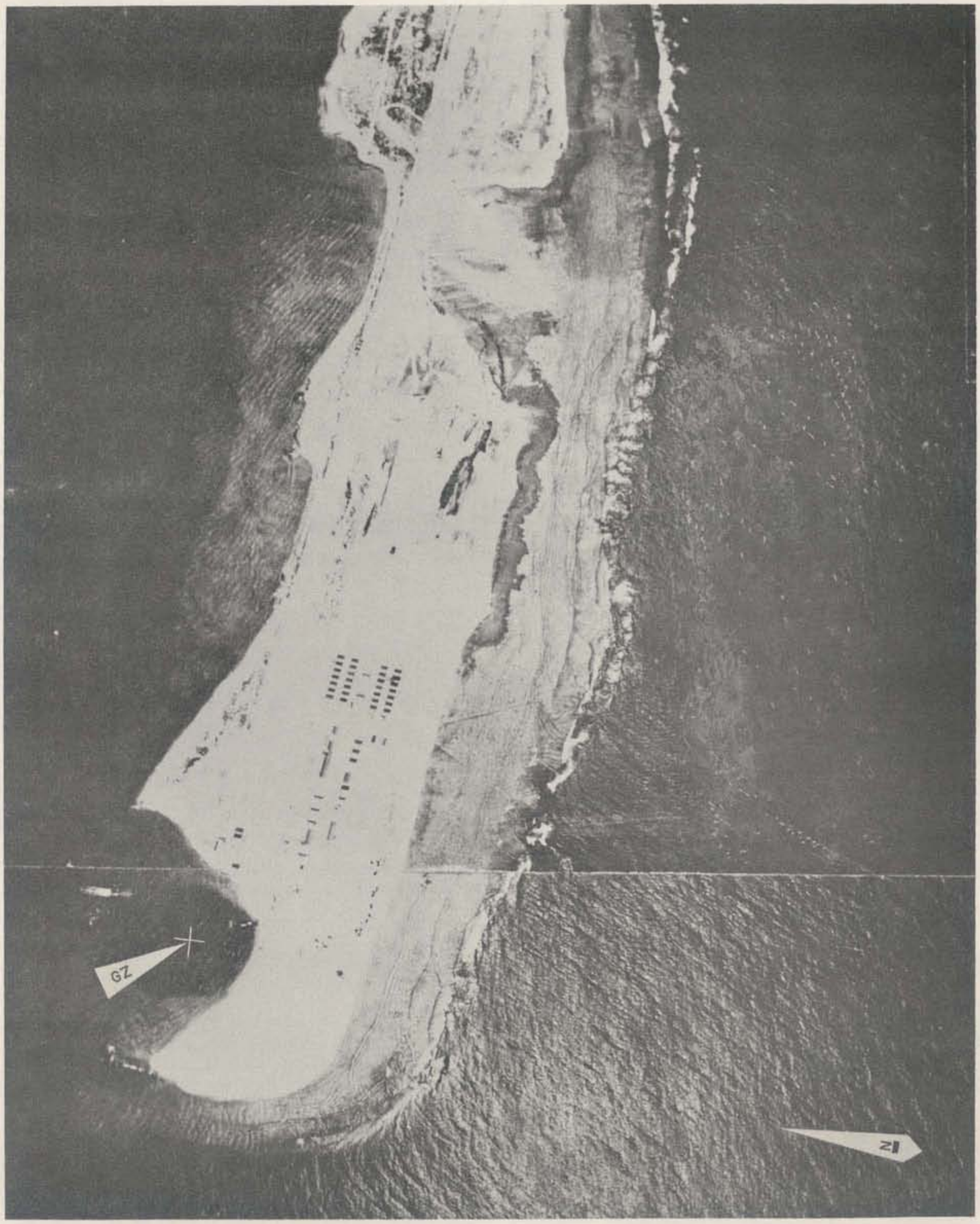

Fig. 14. Koon crater taken two years after the event.[2]

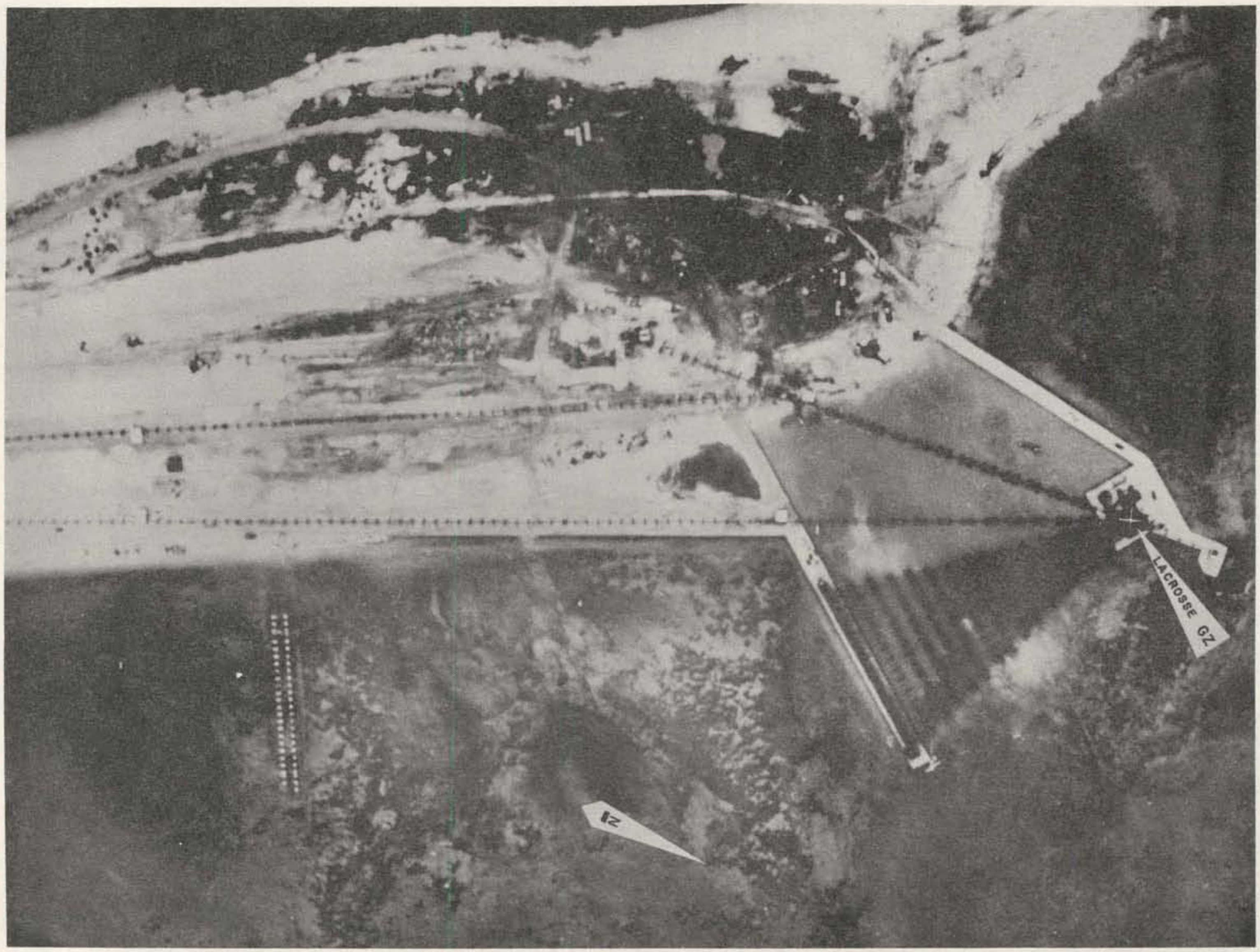

Fig. 15. Preshot Lacrosse area.[2]

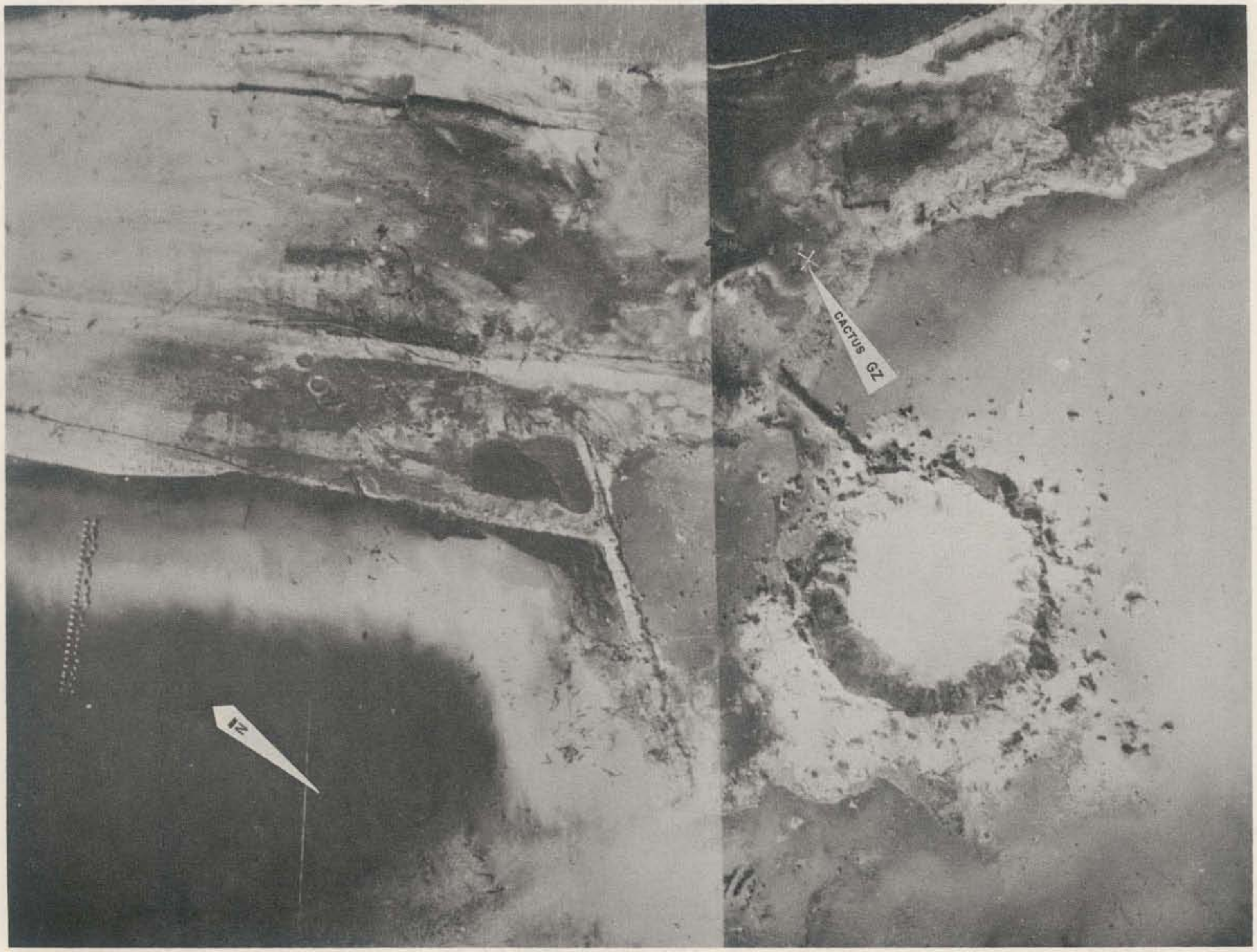

Fig. 16. Postshot Lacrosse area, showing preshot Cactus ground zero location.[2]

Fig. 17. Lacrosse crater following the event.[9]

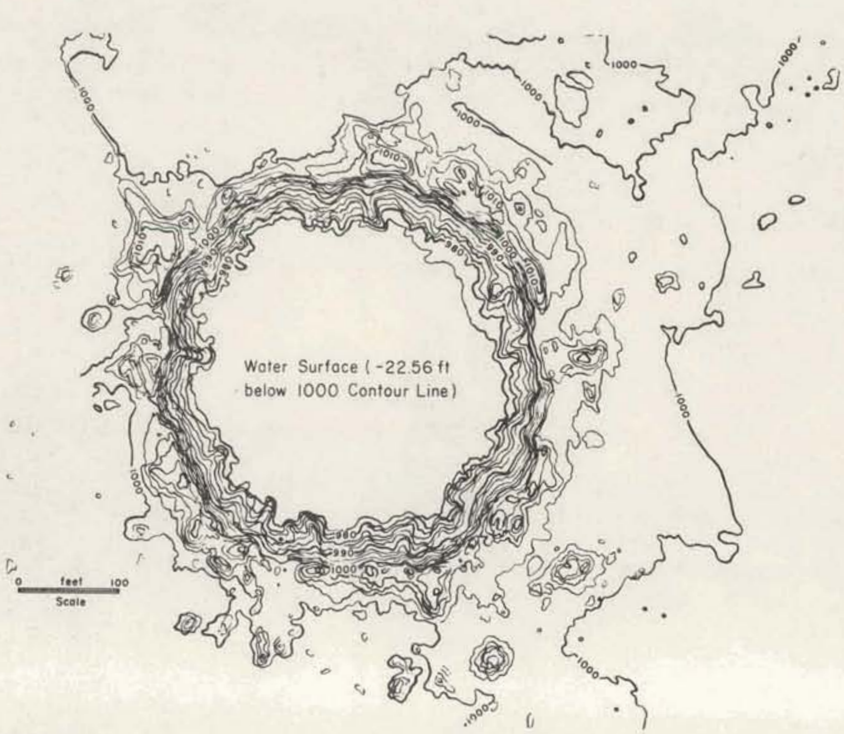

Fig. 18. Photogrammetric contour map of the Lacrosse crater immediately following the event. The 1000-ft contour line is 2.5 ft above the datum plane.[2]

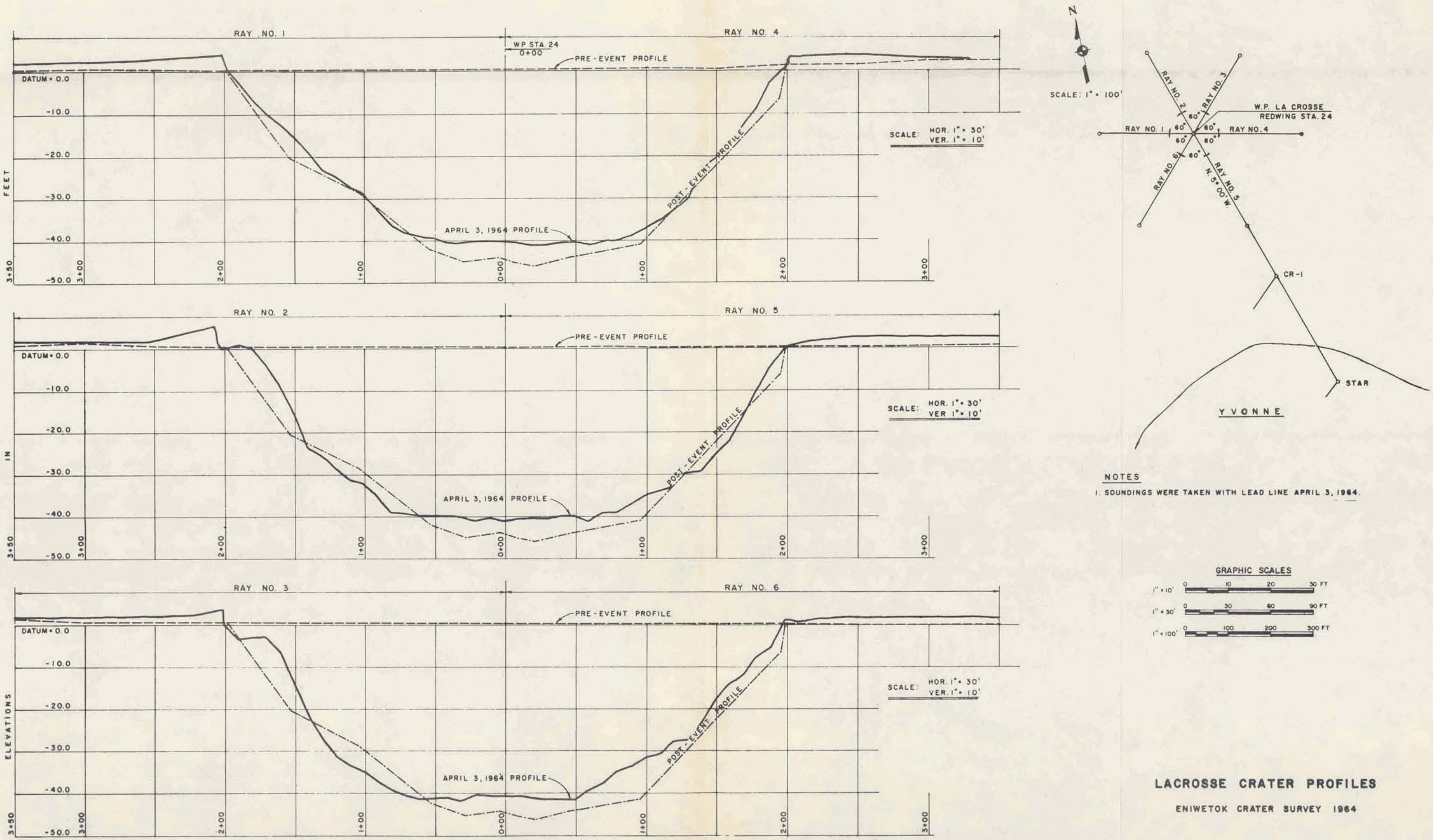

Fig. 19. Preshot, postshot, and 1964 survey profiles of Lacrosse crater.

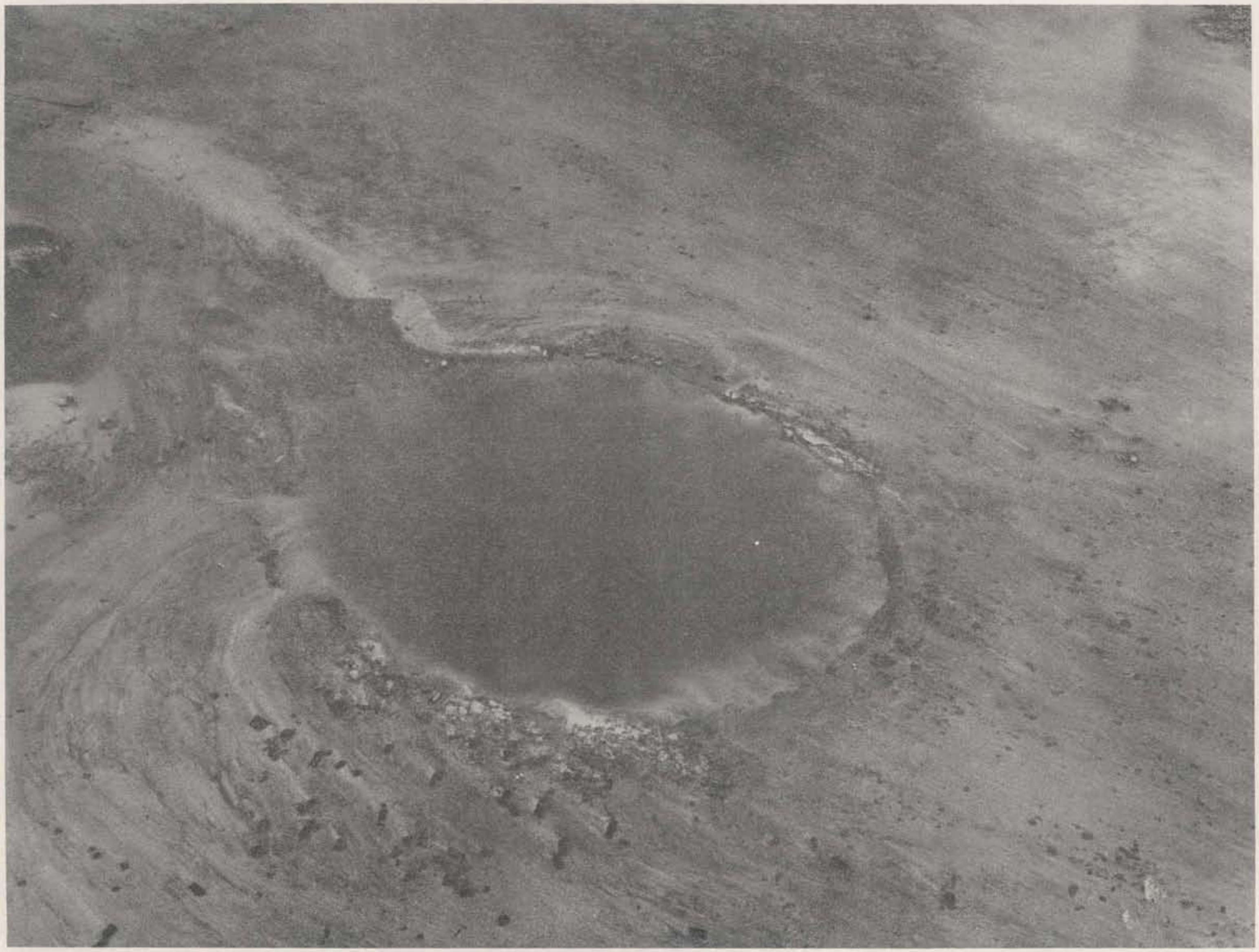

Fig. 20. 1964 photograph of Lacrosse crater.

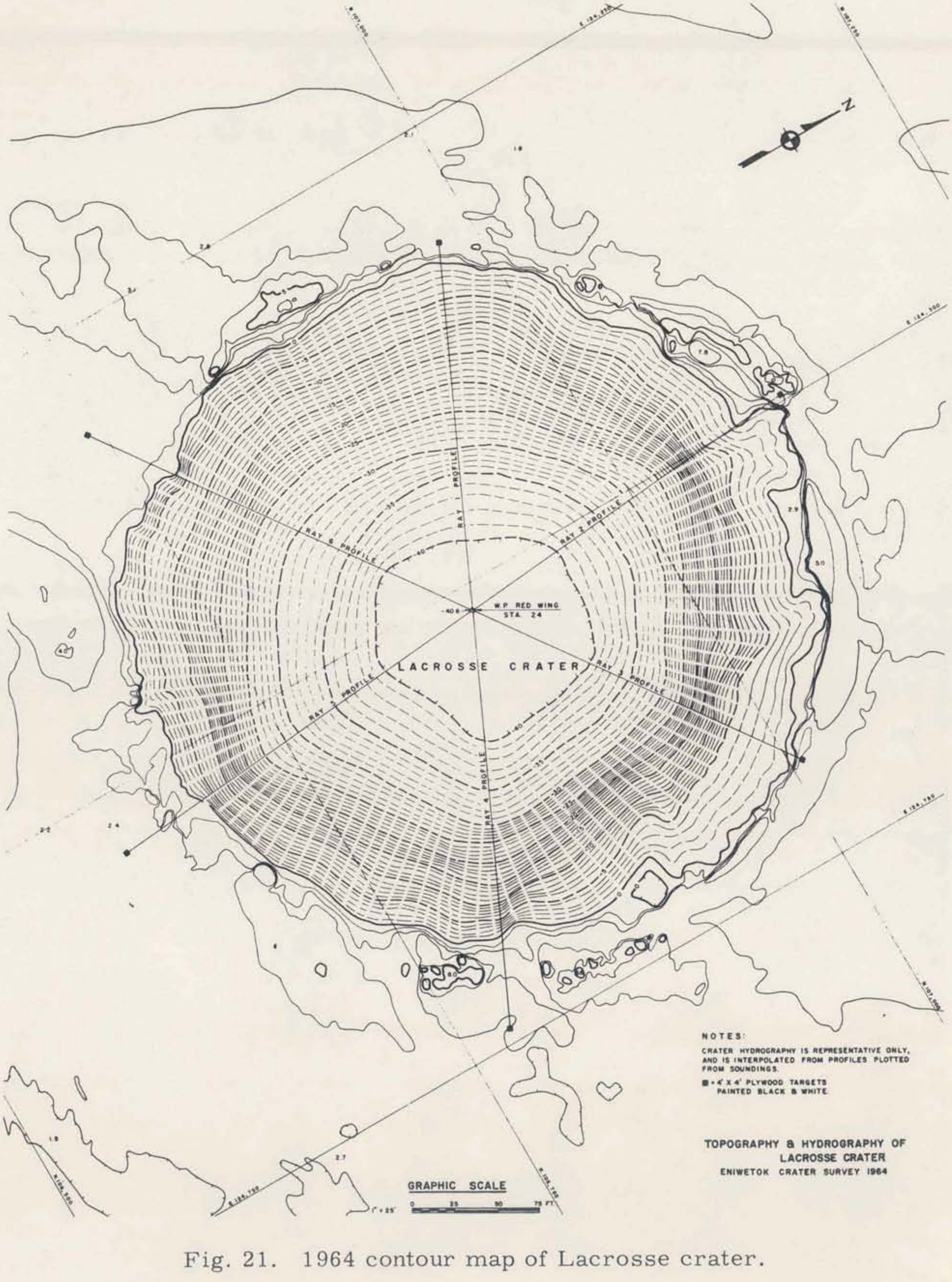

Fig. 21. 1964 contour map of Lacrosse crater.

Zuni

The Zuni shot was a 3.53-Mt device located about 100 ft from the edge of the Koon crater on the island of Tare, Bikini Atoll. The zero point is located just above the pair of buildings near the Koon crater in Fig. 22, 9 ft above the original ground surface. The resulting crater is also shown in this figure. Note the asymmetric shape of the crater in relation to ground zero. The crater radius was about 1240 ft as measured along the original ground surface.[2]

The Zuni crater was smaller than anticipated, both in radius and depth. It is felt that the proximity to the Koon crater altered the normal pattern of shock transmission to the medium resulting in a smaller crater. The crater underwent severe water-washing. No above water lip was present around the crater.

Seminole

The Seminole device was detonated under conditions that are unique and that, in all probability, significantly affected the crater. The device position and surroundings are shown in Fig. 23. The nuclear device was placed in a 15-ft-diam tank which was itself inside a 50-ft-diam tank of water, located 20.5 ft below the water surface. The 13.5-kt device was detonated at a height of 4.5 ft above the original ground surface on the west end of the island of Irene, Eniwetok Atoll, (Fig. 24). The surface of the ground was about 8 ft above the datum plane.[2]

The purpose of the water surrounding the device was to rapidly reduce the temperature of the fireball at very early times and thereby accelerate the time of hydrodynamic separation. This amount of water was thought sufficient to cause separation to occur before the radiation front reached the outside of the tank. This phenomenon would affect the shape of the crater in several ways. Since approximately one-third of the energy of a nuclear device is in the form of radiation, thermal and x rays, for a surface detonation this energy is lost almost immediately and is not available for later conversion to a lower-grade, more useful form of energy. The water surrounding the Seminole device should result in much better utilization of the energy of the device with better coupling of the energy to the ground. This would produce crater dimensions significantly larger than for a normal surface burst. In

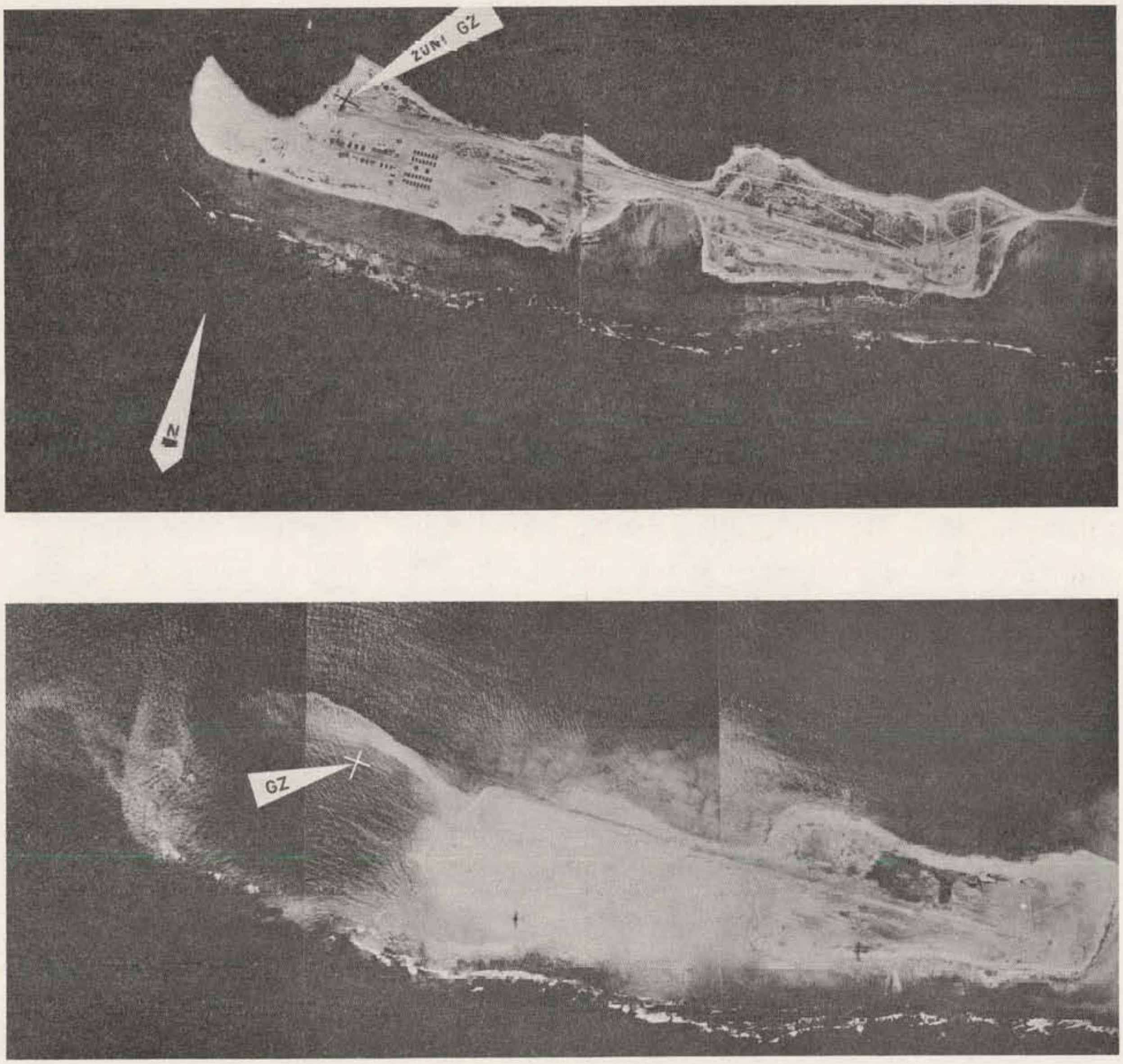

Fig. 22. Preshot and postshot Zuni area.[2]

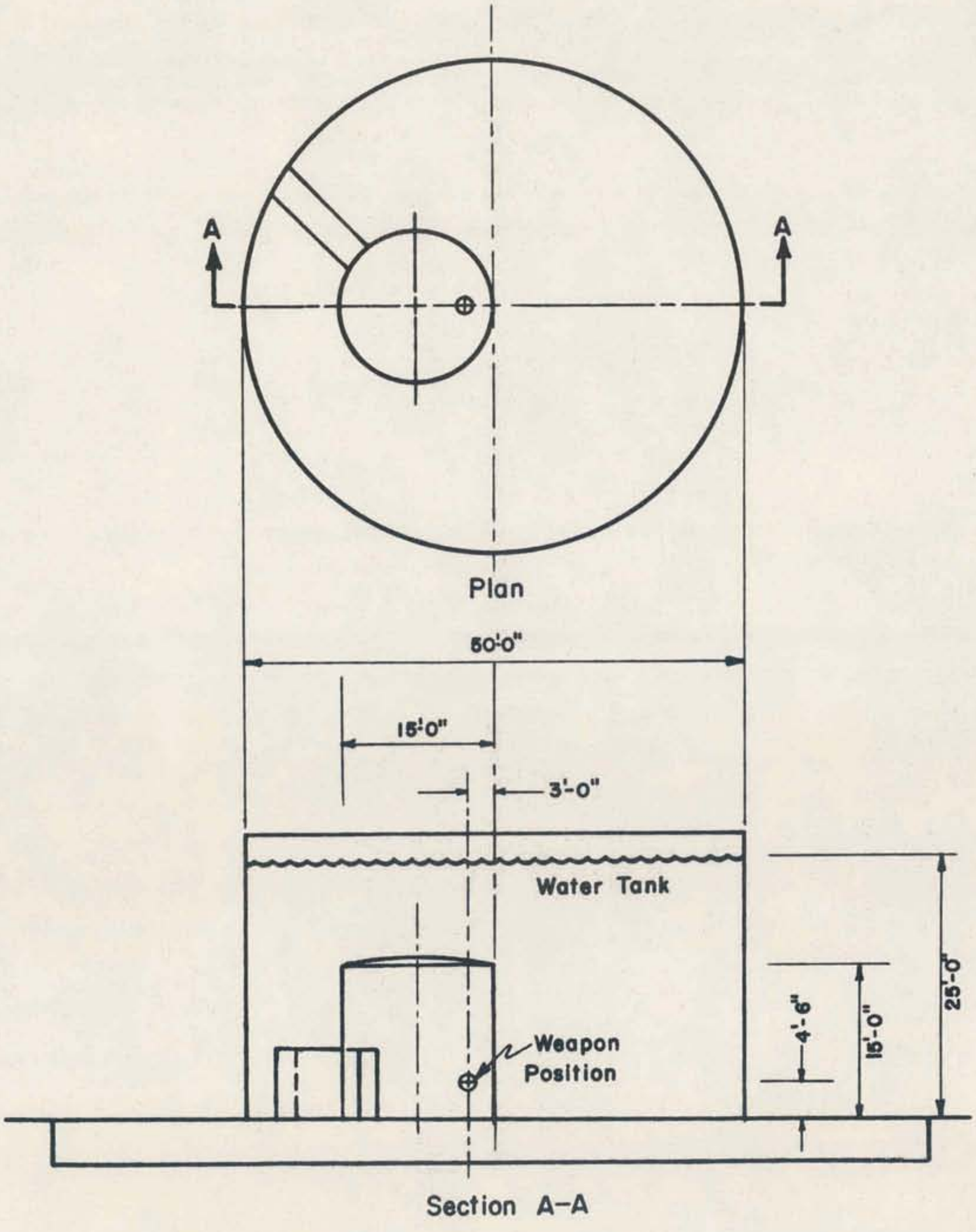

Fig. 23. Device geometry of the Seminole event.[2]

Fig. 24. Preshot Seminole area.[2]

addition, due to the asymmetry of the device in the water tank, it would be expected that the crater would be asymmetric.[2]

Figure 25 is a postshot photograph of the Seminole crater taken the day after the shot. Figure 26 is a plot of postshot profiles obtained with lead-line soundings. The relationship of the rays to the asymmetry is illustrated in the upper right corner of the figure. In the direction of the longest water path, i.e., rays 1, 2, 3, and 4, the average crater radius measured at original ground level was 390 ± 30 ft. For rays 5 and 6, for which there was a much shorter water path for the radiation and shock to traverse, the average radius was 255 ± 25 ft. This large deviation is undoubtedly due to the asymmetric presence of the water tank. The bottom of the crater was very flat over a radius of 150-200 ft at a depth below original grade of 31 ft. There was a small lip approximately 7 ft high above original ground level, 15 ft above the water surface.

Figure 26 also illustrates the results of the 1964 survey using lead-line soundings. Note that rays 3 and 6 seem to be about 75 ft to the left of the true position indicating a probable survey error. Ray 5 shows that slope failures of the crater have occurred, although the crater bottom has only filled in a few feet. The medium appears to consist of weakly cemented sand, as shown in Table III. Several ground subsidences appeared around the crater shortly after the shot. Rays 1 and 2 indicate the slopes have filled in from an external source, probably from the erosion of its entrance channel. Figure 27 is a 1964 photograph of the crater. Figure 28 is a contour map of the crater made from surveys and photographs from the 1964 study.

Tewa

Tewa was a 5.01-Mt device fired on a barge in 20 ft of water near the reef between Charlie and Dog Islands, Bikini Atoll. The height of burst above the water surface is not known; the height of burst has been assumed to be 20 ft. The resulting crater opened on one side to deep water and therefore was not too well defined. However, the deepest point, which was under the detonation point, was 129 ft below the surface with a ridge at a depth of about 80 ft on the lagoon side. A postshot photograph of the crater is shown in Fig. 29. The radius of the crater, defined on the reef side of the crater only, was about 2000 ft. There was no lip above water.[2]

Fig. 25. Postshot Seminole area.[2]

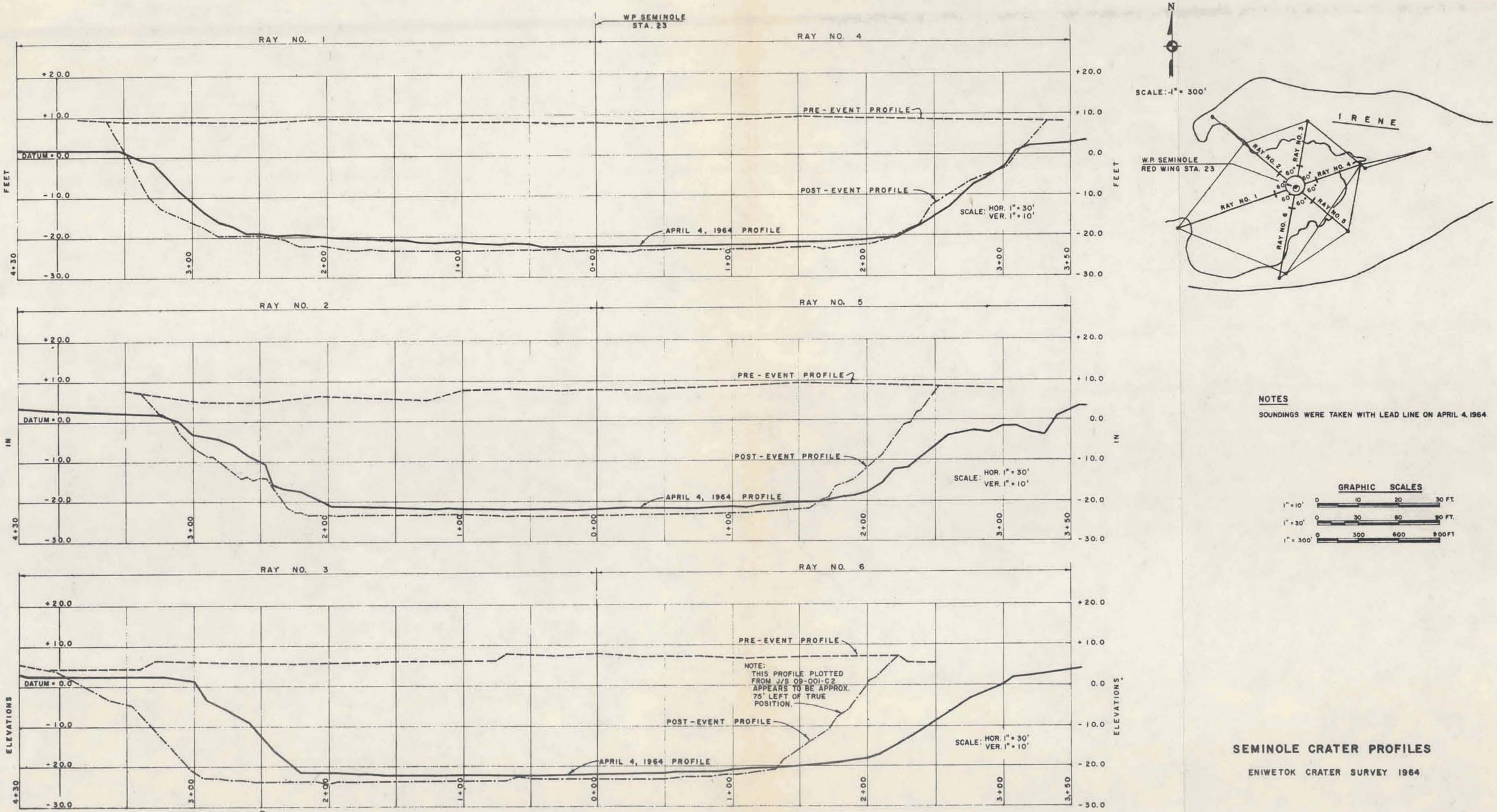

Fig. 26. Preshot, postshot, and 1964 survey profiles of Seminole crater.

Fig. 27. 1964 aerial photomosiac of the Seminole crater.

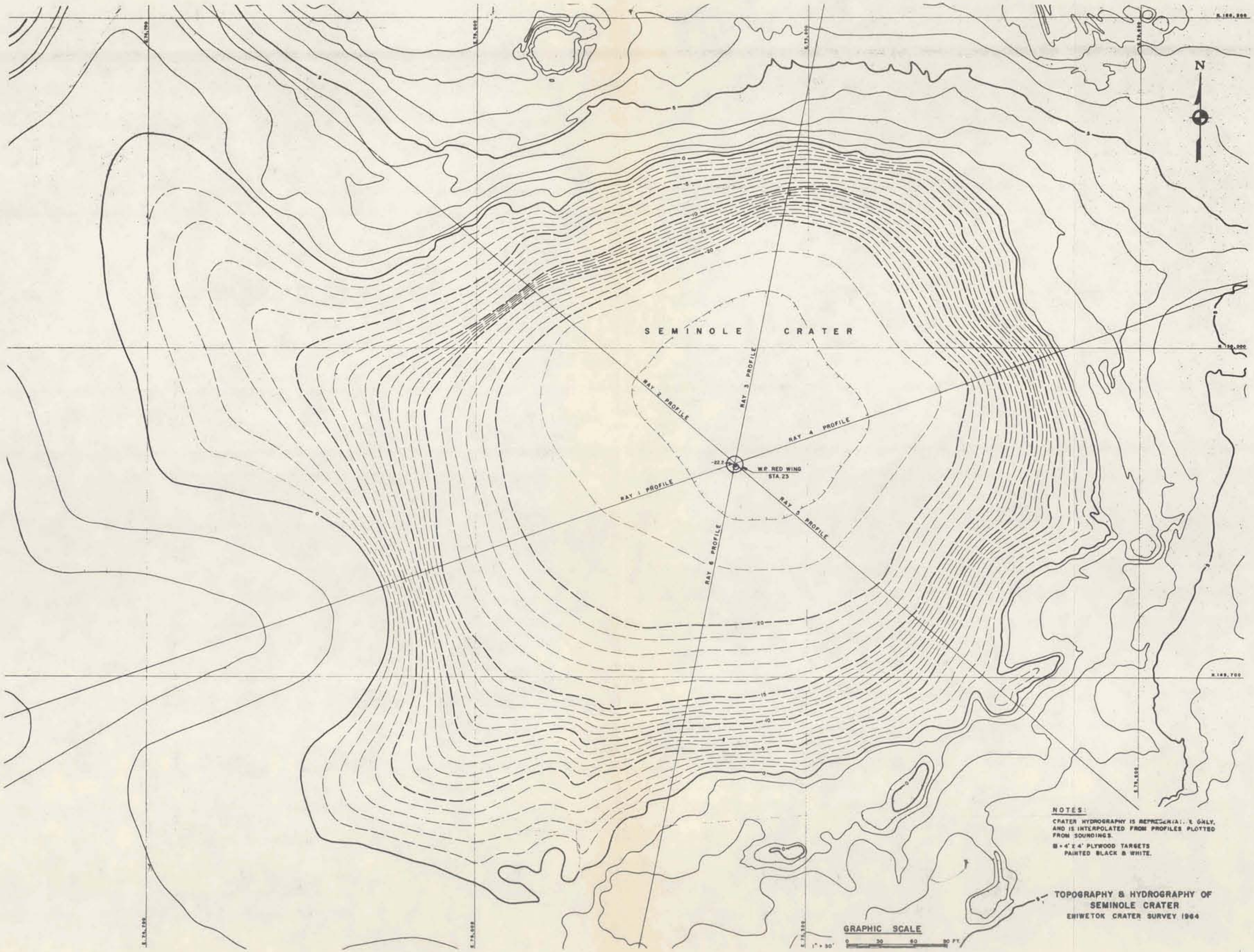

Fig. 28. 1964 contour map of the Seminole crater.

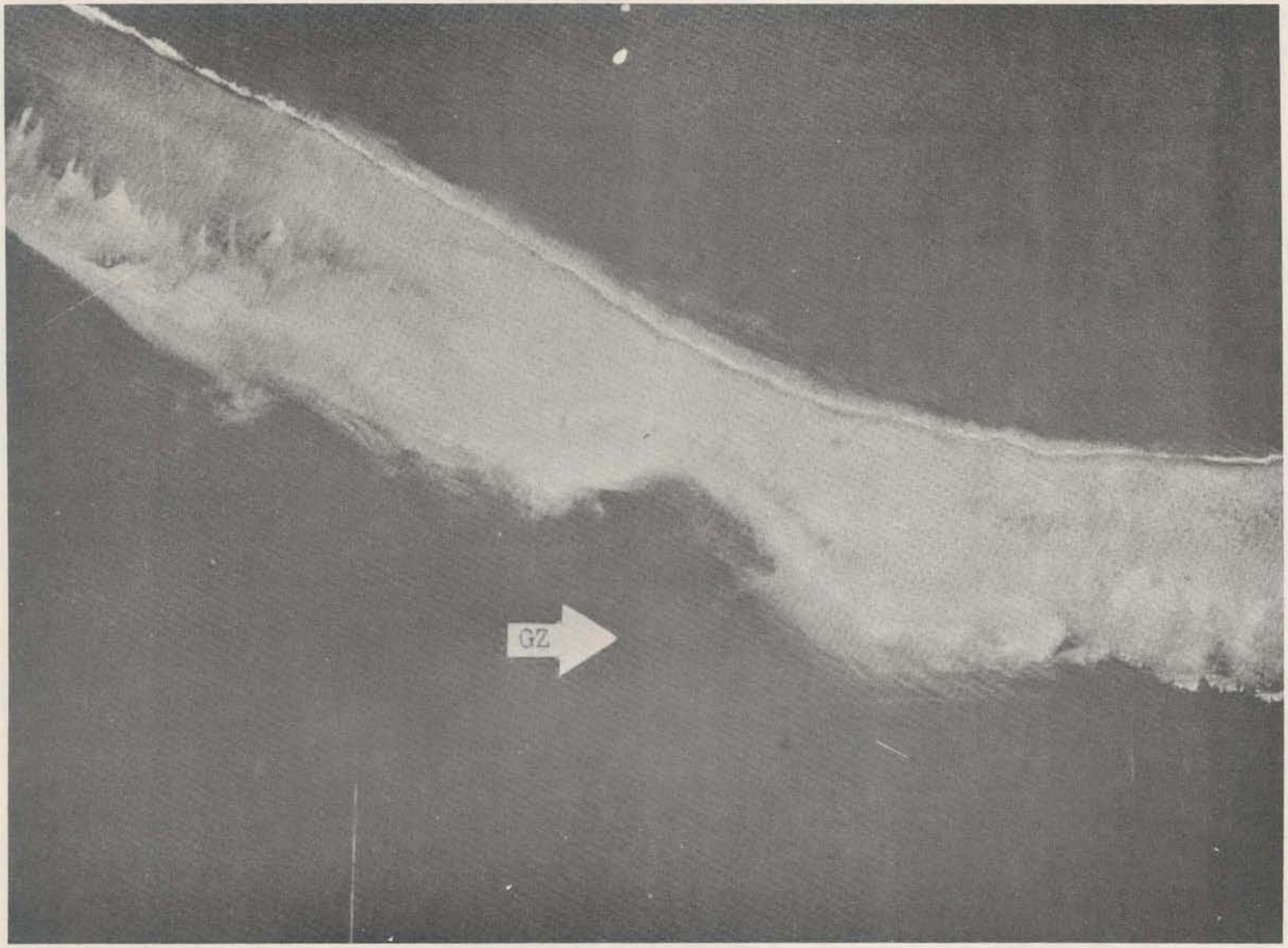

Fig. 29. Postshot Tewa area.[2]

Koa

The Koa device was a 1.37-Mt nuclear explosive detonated on the west end of the Gene-Helen Island complex, Eniwetok Atoll, at the edge of the Mike crater as shown in Fig. 5. The device was placed 3 ft above the original ground surface in the center of a 30-ft-diam tank of water. The water height above the device was 8.3 ft. This produced the same effect as the water tank on Seminole, although to a much smaller extent, because of the larger yield. The location of ground zero is shown in Fig. 30. The crater breached to the lagoon and was severely water-washed by the returning volume of water. The radius of the crater was estimated to be 1825 ft. Figure 31 is a postshot photograph of Helen Island, showing the edge of the crater. This area, preshot, is shown on the right of Fig. 30. The depth measured by a lead line 4 days after the shot was 135 ft. Fathometer readings gave a depth of 87 ft, a difference which was undoubtedly due to suspended mud and silt in the crater.[3] The size of the water tank would not be large enough to allow the hydrodynamic shock to outrun the radiation front inside the tank, but it would add a significant mass to the fireball and change its size considerably. In addition, the degradation of the energy would put more energy into the form of hydrodynamic energy which could be used for cratering.

The frontispiece is a 1964 photograph showing the Koa crater merging with the Mike crater. The 1964 Koa survey was made by fathometer, with lead-line soundings to confirm fathometer readings. The profile of the crater is shown in Fig. 32. It can be seen that the greatest change that has taken place has been a silting-up of the crater to a present depth of about 105 ft. This is similar to the change in the adjoining Mike crater. It is apparent that the suspended mud and silt in the crater which originally gave incorrect fathometer readings, settled and consolidated over the years to give the crater its present depth.

Cactus

Cactus was a 18-kt nuclear device detonated on the northwest end of the island of Yvonne near the Lacrosse crater. The drilling log given for Yvonne Island in Table I was for a hole 400 ft southwest of ground zero and indicates that the medium for Cactus as well as for the nearby Lacrosse shot was quite hard and rocklike. The device was detonated 3 ft above the surface of the

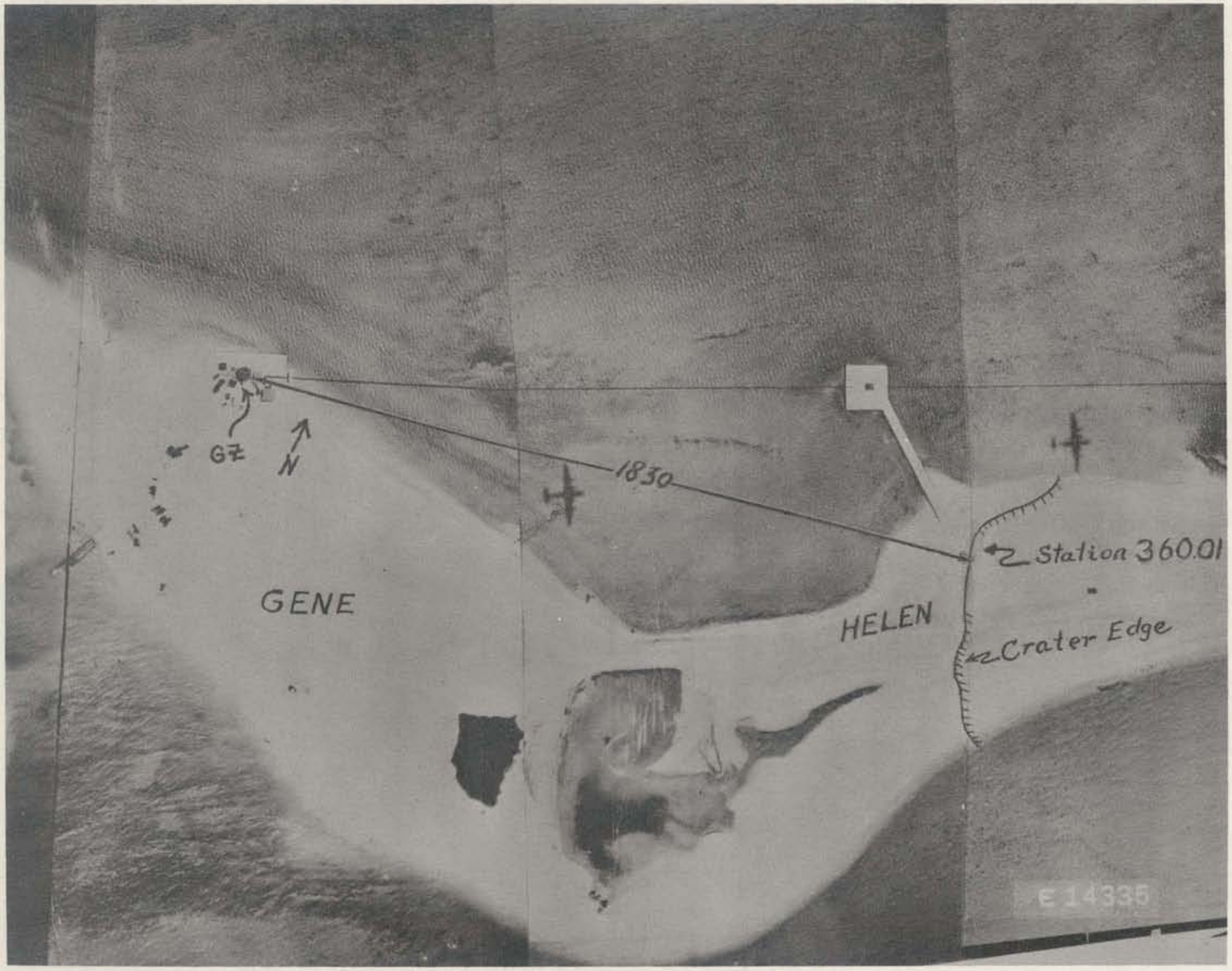

Fig. 30. Preshot Koa area. Note the outlined west edge of the resulting crater.[3]

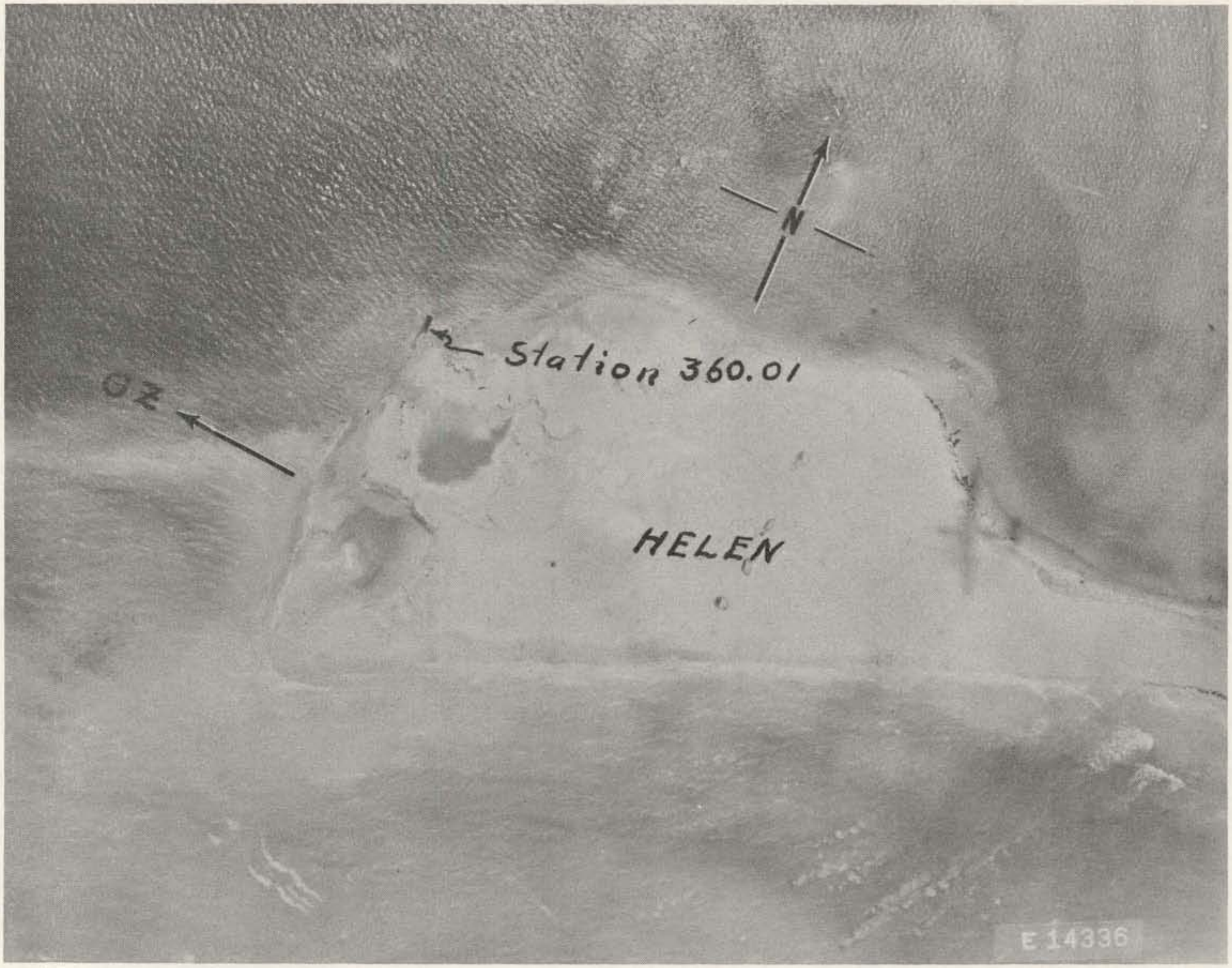

Fig. 31. Postshot aerial photograph of the west edge of Koa crater.[3]

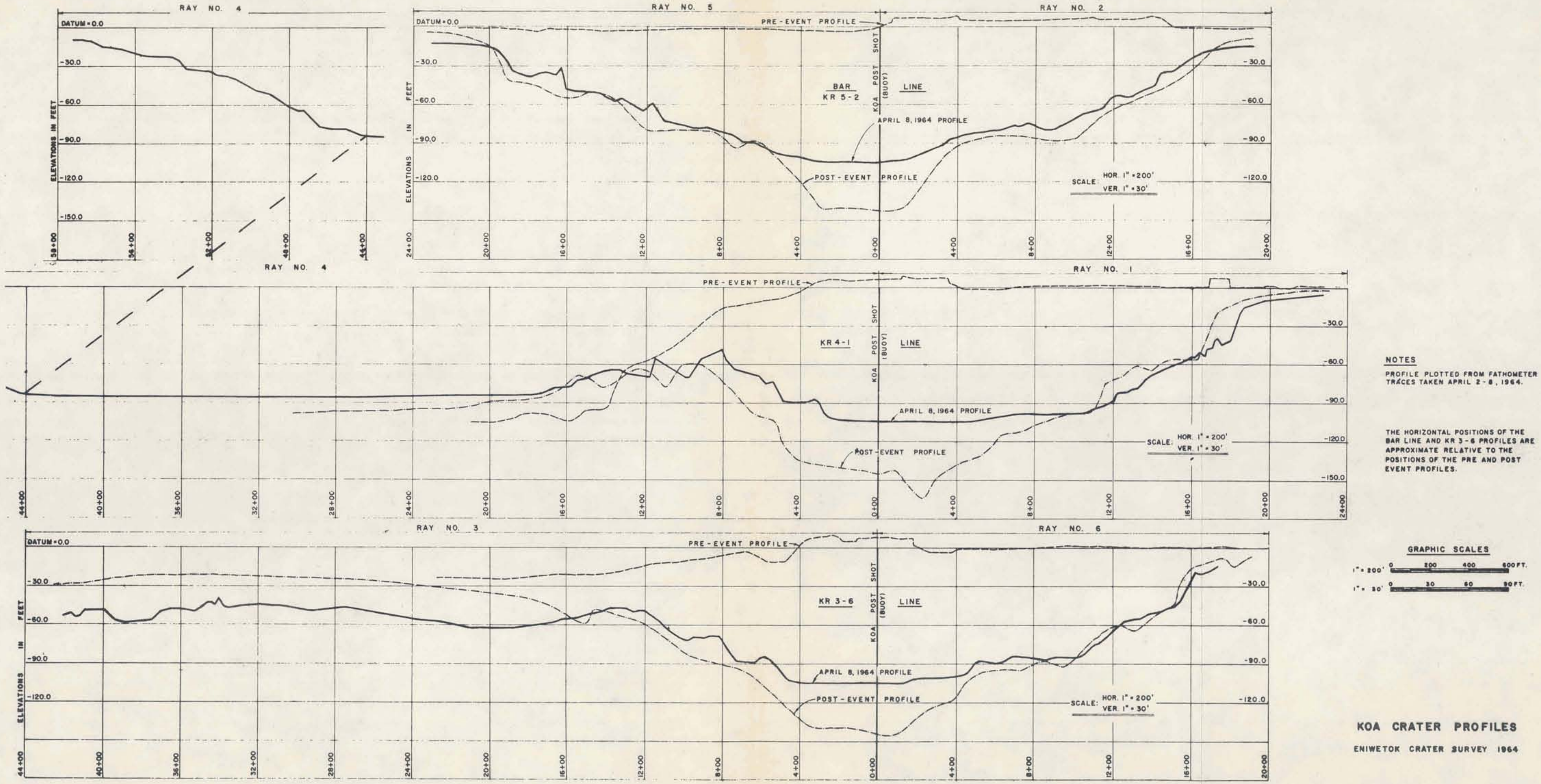

Fig. 32. Preshot, postshot, and 1964 survey profiles of Koa crater.
Note KR 4-1 line passing through section of Mike crater.

island which was 7 ft above the datum plane.[3] The zero point was in a small building located as indicated in Fig. 16.

Figure 33 shows the Cactus crater immediately after the detonation (Cactus is on the right, Lacrosse on the left). The average crater radius, measured from aerial photographs, was 185 ft. This is presumably measured at the level of the water that filled the crater postshot. There was no evidence of water-washing due to the elevation of the surface and the existence of a lip on all sides except to the north. There were hummocks as high as 25 ft. These can be observed in Fig. 34, a postshot contour map of the crater area. The depth, measured with lead line from a helicopter 3 weeks after the shot was 36 ft, measured from the original ground surface.

Figures 35 and 36 are 1964 photographs of the Cactus crater. Note the high lips which were produced by the detonation. These lips have gradually eroded by undercutting action of the waves, forming a small beach around the crater. This is better illustrated by the survey profiles shown in Fig. 37. The 1964 survey was conducted by lead-line soundings. The crater has not appreciably changed from the post-event profile. Along Rays 1 and 6, which are open to the reef, a small amount of silting-up from an external source is evident. Figure 38 is a contour map of the crater made from the 1964 aerial stereophotogrammetric photographs and the lead-line surveys.

<u>Oak</u>

Oak was an 8.9-Mt device fired on a barge about 4 miles southwest of Alice Island off the edge of the reef (Fig. 39). The device was detonated about 6.5 ft above the water level. Approximately one-half of the resulting crater breached to the lagoon as shown by Fig. 40, a 1964 photograph of the crater. Preshot and postshot surveys were taken along six rays of the crater as shown in Fig. 41. The radius of the crater, along the reef side, was about 2200 ft. The depth of the crater, as measured by fathometer, was 183 feet.[3]

The crater was not surveyed in 1964 since it was decided that meaningful data could not be economically obtained. The tripod control points used in the original survey had been removed. Only a small portion of the crater is visible from the air, and high-order control from several miles away would have been necessary.

Fig. 33. Lacrosse (left) and Cactus (right) craters following the Cactus event.

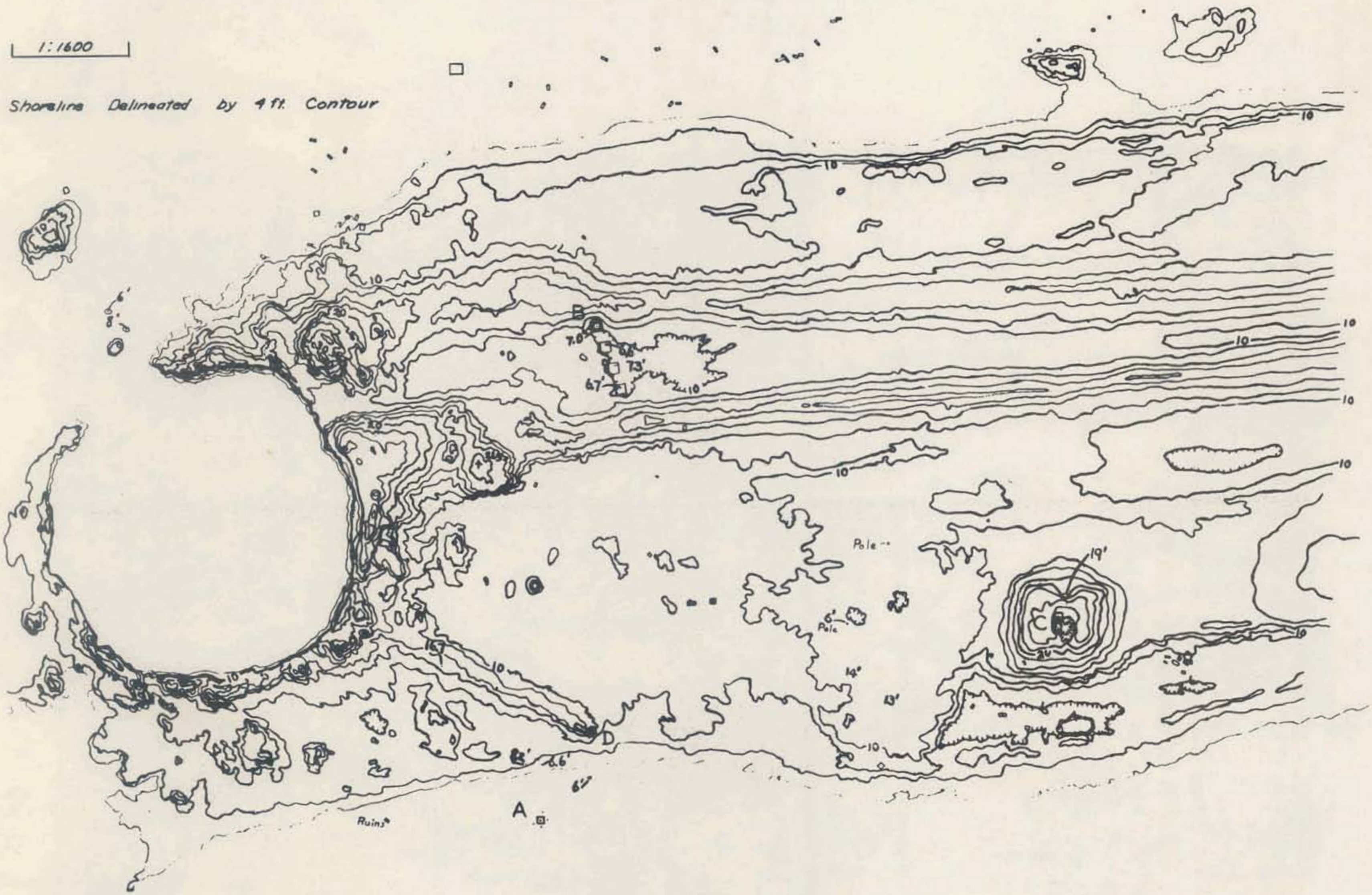

Fig. 34. Postshot contour map of the Cactus crater and a portion of Yvonne Island.[3]

Fig. 35. 1964 photograph of the Lacrosse (left) and Cactus (right) craters.

Fig. 36. 1964 photograph of the Cactus crater and lip. Note the beach formed by lip erosion in the crater. Lacrosse crater is seen in left background.

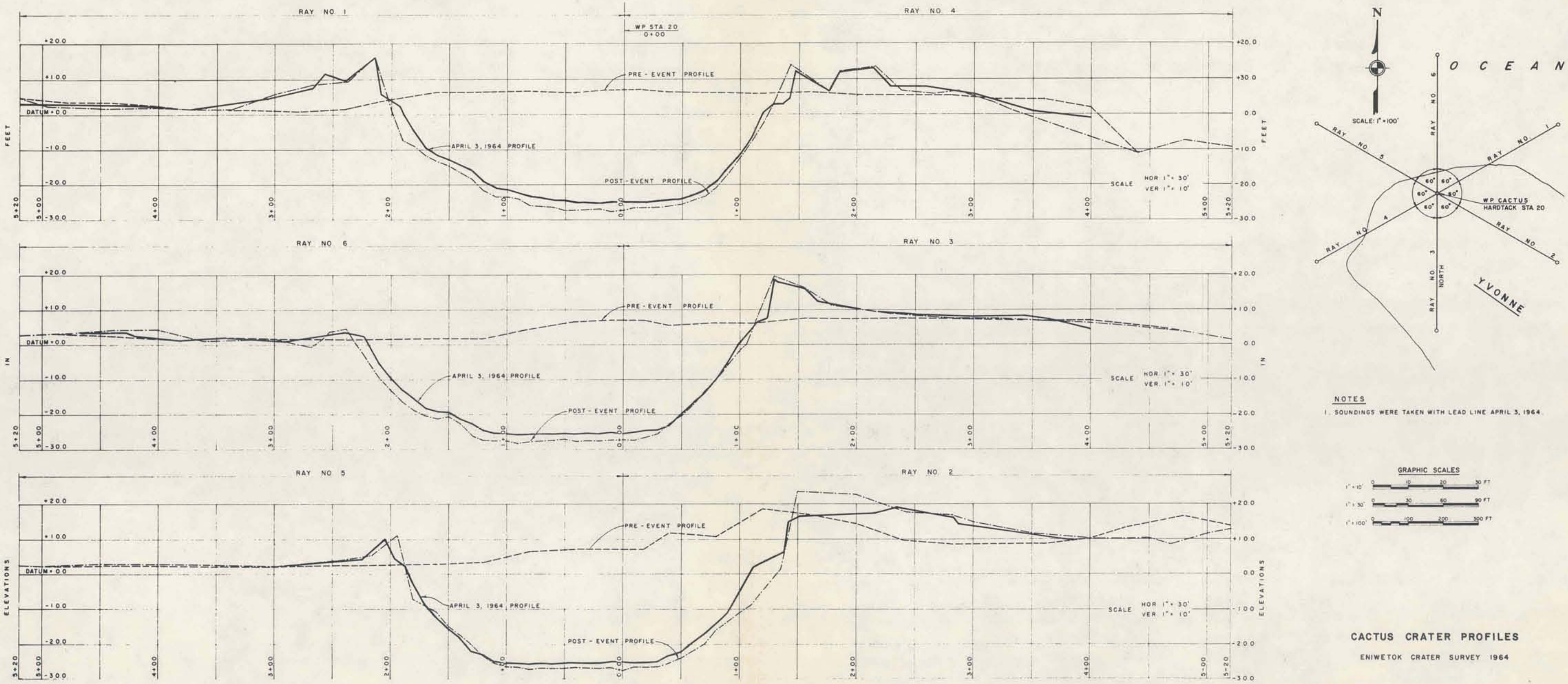

Fig. 37. Preshot, postshot, and 1964 survey profiles of Cactus crater.

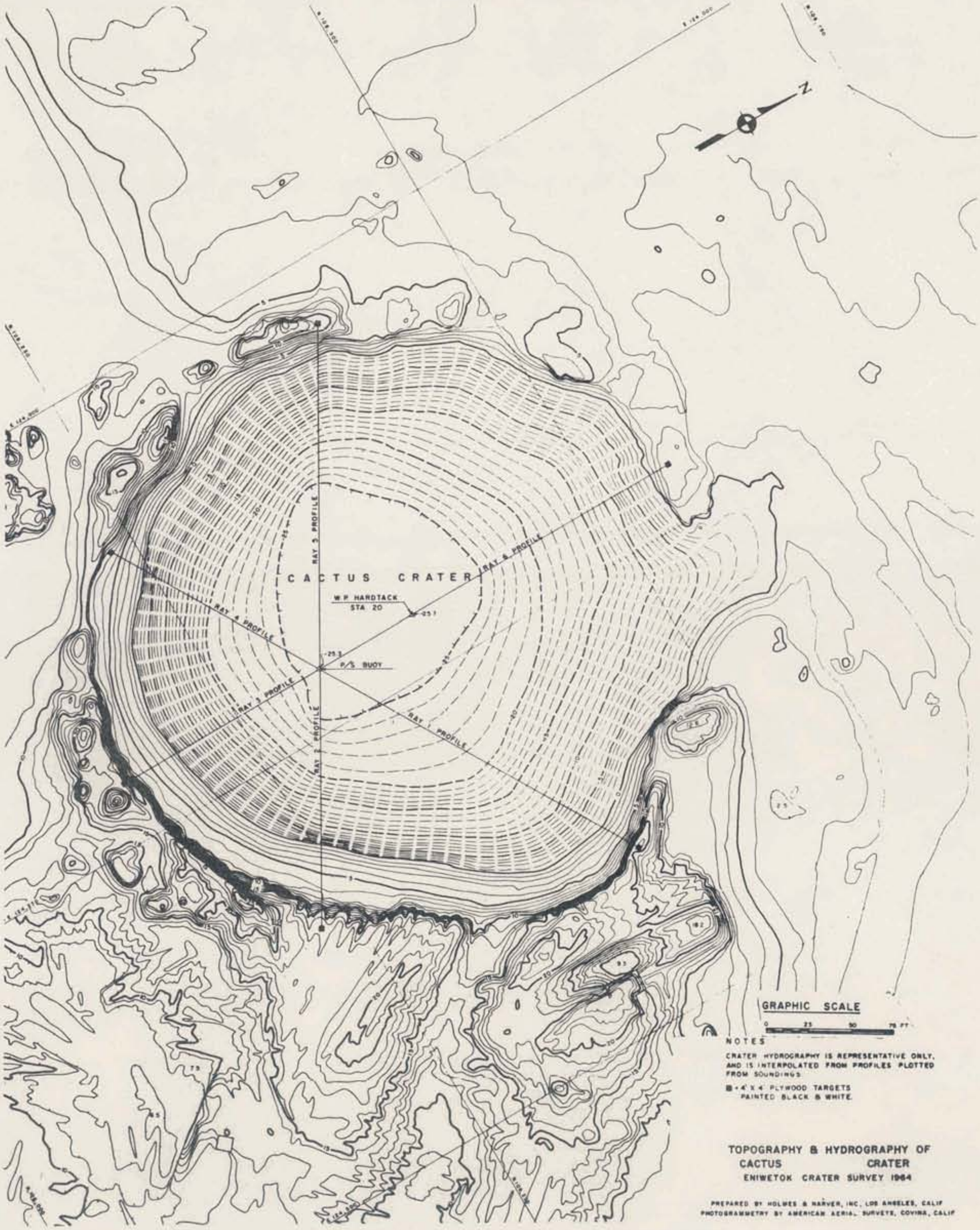

Fig. 38. 1964 contour map of Cactus crater.

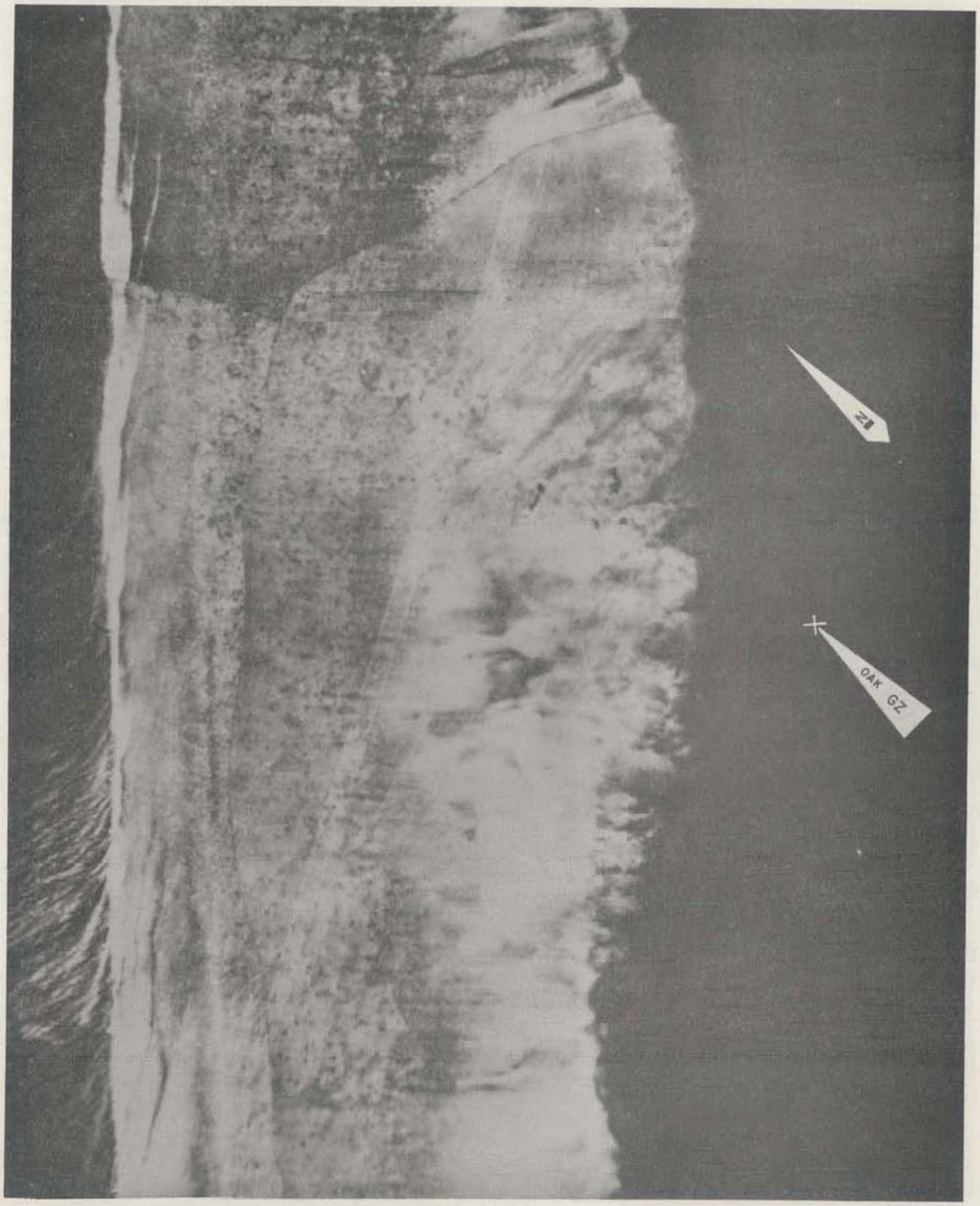

Fig. 39. Preshot Oak area.

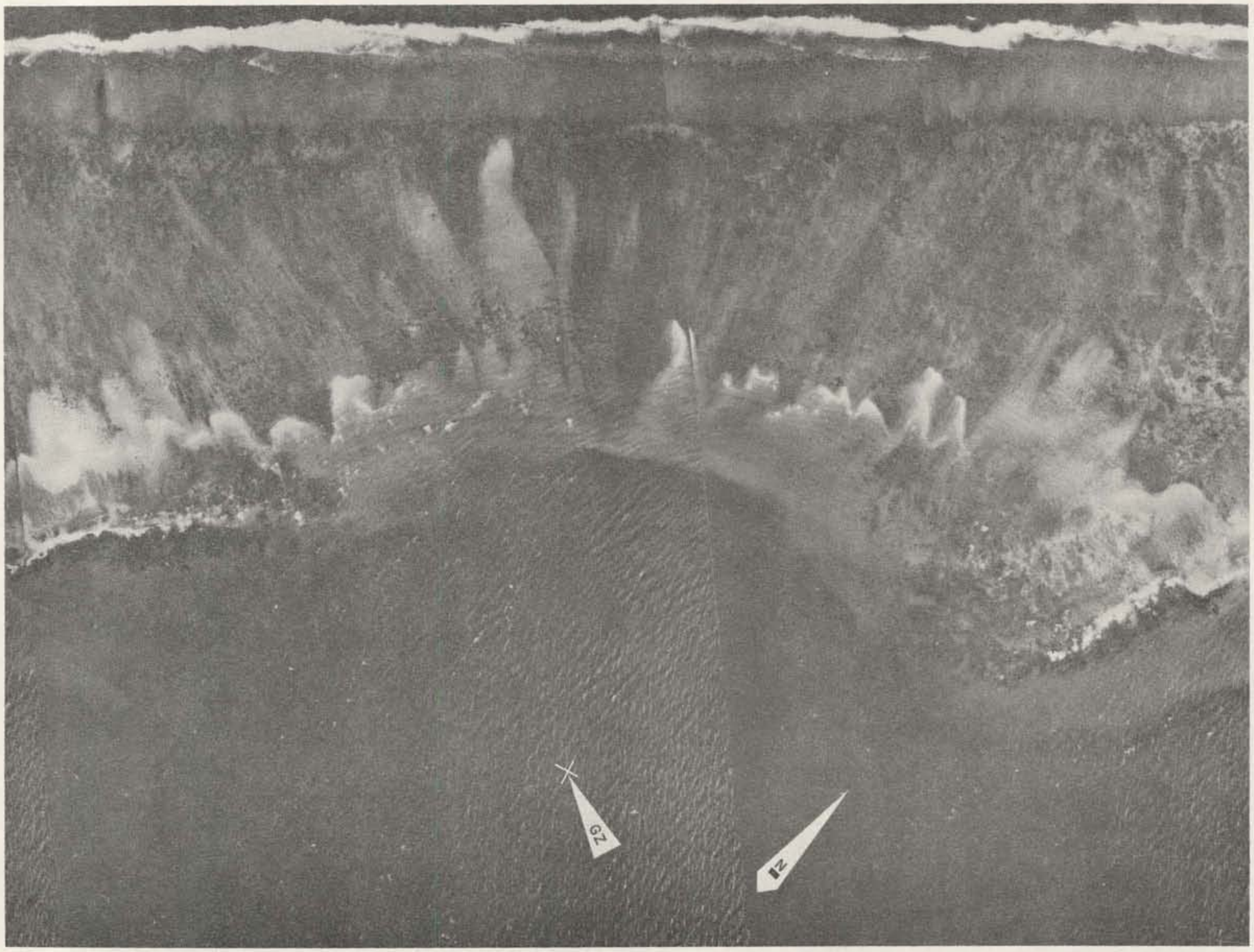

Fig. 40. 1964 photograph of the Oak crater.

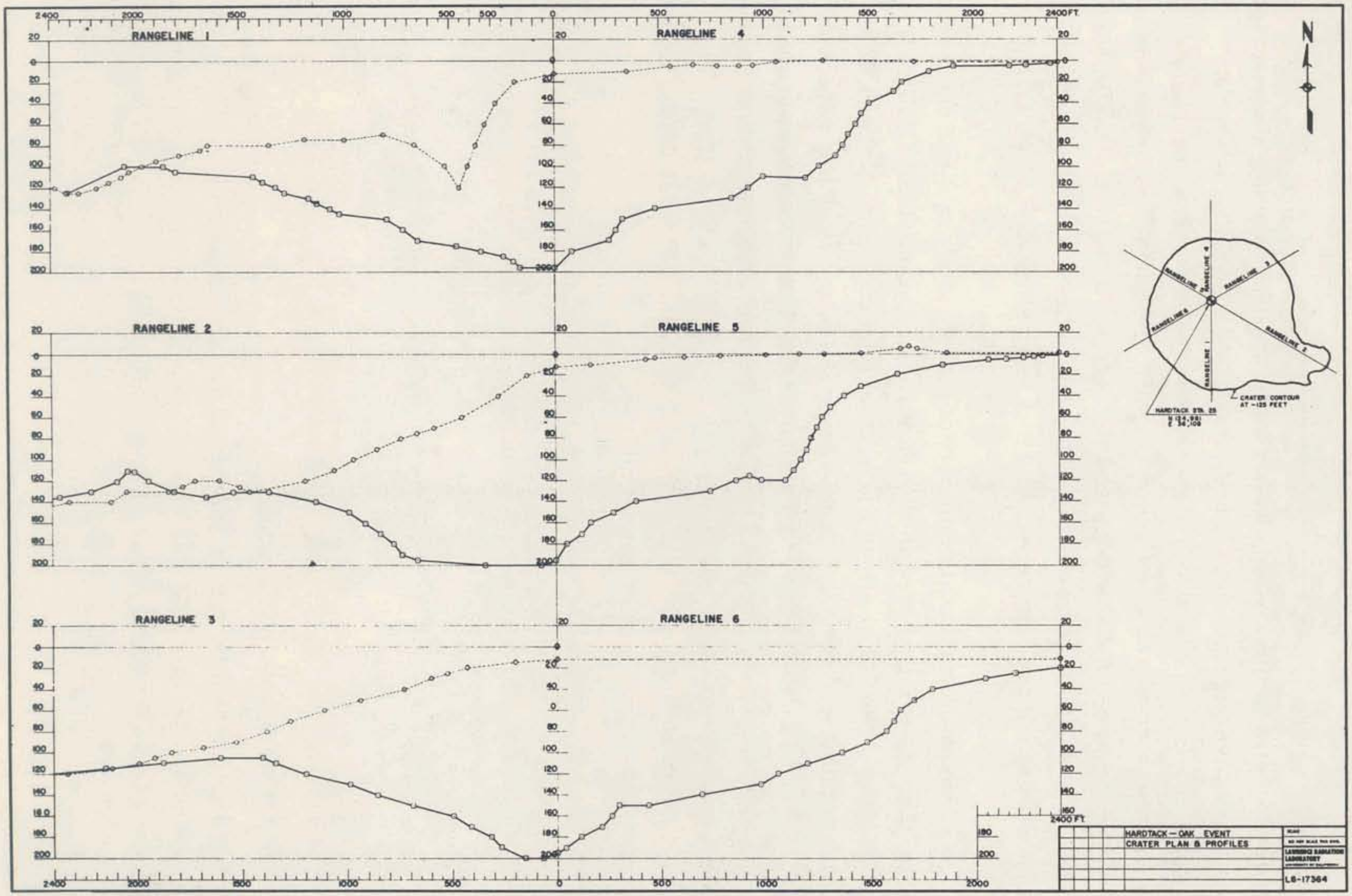

Fig. 41. Preshot and postshot survey profiles of the Oak crater.[3]

RESULTS

Cratering Curves

The dimensions of the craters which were produced by the near-surface detonations were investigated as to the applicability of scaling laws. Although this information is not directly applicable to Plowshare technology, since maximum crater dimensions occur at optimum burial, the relationships will increase present knowledge and provide an insight into the mechanics of cratering. The various geometries of the detonations were so diverse that considerable scatter would be expected in any relationships which are developed.

Figure 42 shows the relationship between explosive yield and the radius and depth for the craters involved in this study. Also included is Jangle S, a 1.2-kt detonation fired 3.5 ft above the ground surface at the Nevada Test Site. This data point was not used in this analysis because of the difference in the medium but is included for comparison. The Koa and Seminole shots were also discounted because of the peculiar circumstances surrounding these shots (see discussions of these shots above). As mentioned earlier, the depth of the Koon crater is probably shallower than the original depth, and the Zuni crater was also smaller than expected.

Radius

As shown in Fig. 42, a fairly good fit to the radius data can be made by the equation

$$R = 50\ W^{1/2.5},$$

where

R = crater radius in feet, and
W = yield in kilotons.

It is interesting to note that a number of fireball phenomena also scale as the 2.5 root of the yield. The radii at thermal minimum, R_{TM}, and breakaway, R_B, are generally observed to follow the laws[10]:

$$R_{TM} \sim 90\ W^{1/2.5}$$

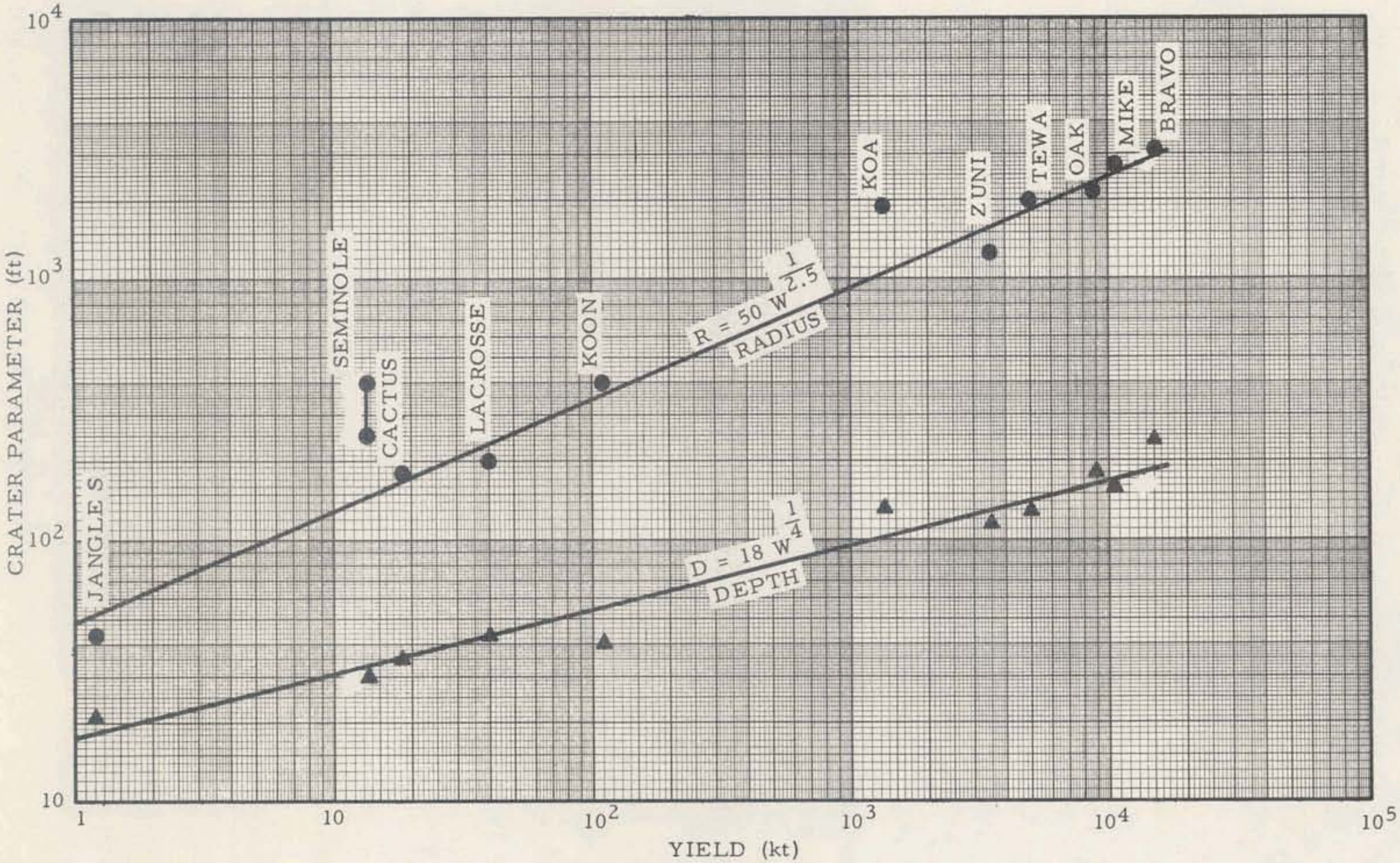

Fig. 42. Crater parameters (radius and depth) vs event yields.

and

$$R_B \sim 145\ W^{1/2.5},$$

respectively. If it is assumed that the radius at hydrodynamic separation, R_{HS}, also follows this scaling, the relationship would be:

$$R_{HS} = 12\ W^{1/2.5}.$$

Thus, crater radius would correspond to a point where the fireball radius is about midway between hydrodynamic separation and thermal minimum.

During this early history of the detonation, the shock wave is essentially identical with the surface of the fireball. Since the crater for explosions at or near the ground surface is believed to be primarily due to compaction and plastic deformation of the medium in response to the overpressures laid down by the fireball, it would be expected that crater radii would scale in a manner similar to fireball radii. Pressures at a fireball radius of 50 $W^{1/2.5}$ would be of the order of 1.5 kilobars,[11] which would be sufficient to induce rock breakage and deformation.

Several physical factors would also affect the radius of these craters. The type and composition of the various media as well as the geometry of the shot (such as whether ground zero was on an island, a causeway, or a barge), would influence crater size. Also the effect of water-washing could alter crater radii considerably. However, the strong relationship shown in Fig. 42 indicates that the effect of these variables is small compared to the dominant effect of the yield of the detonation.

It should be noted that data from the recent Flattop and Air Vent series of H. E. cratering shots in the playa of Frenchman Flat at NTS,[12] show a crater radius dependence of about $W^{1/2.8}$ for surface bursts. The scaling dependence of depth appears to be about $W^{1/3.2}$.

Depth

The relationship between crater depth and yield is also shown in Fig. 42. This indicates a scaling factor of $W^{1/4}$. This scaling factor was also observed in other studies.[10] Normally, it would be expected that this parameter would scale similarly to the radius. However, due to many physical phenomena peculiar to these shots, resulting craters are somewhat shallower.

Perhaps the most dominant effect would be that of hydrostatic pressure. Since hydrostatic pressure increases with depth, the deeper blast energy penetrates into the medium, the greater will be counteracting hydrostatic pressure. This will result in a less efficient excavation and subsequent shallower craters as the yield is increased.

Another important phenomenon would be the effect of water-washing. It is interesting to note that the unwashed craters (Lacrosse and Cactus) have parabolic shapes. All the washed craters have conical shapes or broad flat bottoms like Seminole. This effect would be a logical result of water-washing. Material washed back into the crater would hit and roll down the crater slopes until it reached a stable position. Rock would reach a rather steep angle of repose, which would produce a conical shape. Sand and finer-grained material would attain a very flat angle of repose on the slopes or go into suspension and fill in the bottom of the crater.

Inhomogeneities of the medium can also affect the crater depth. These can be caused by collapse of the large cavities in the geologic structure of the atoll (see p. 7). This collapse could cause local subsidences in or around the crater. For example, the deepest part of the Mike crater was offset 300 ft from ground zero, suggesting a localized subsidence.

Figure 31 shows two subsidences adjacent to Koa crater. Similar subsidence was observed around the Seminole crater. In addition to the collapse of large cavities in the atoll, the shock waves travelling through the medium could cause densification of metastable zones of material which could be transmitted to the surface as subsidences.

Height of Burst

The data in Table IV were scaled as indicated on Fig. 42 and plotted against the scaled height of burst as shown in Fig. 43. A general trend of increasing crater parameters with decreasing height of burst can be detected, although the scatter is very large. The only exception in both cases is the Zuni crater which was smaller than expected due to the peculiar geometry of the shot (see p. 37). However, the maximum spread is about 30% from the mean in both cases. With the many other variables, such as the actual burst heights of Tewa and Oak, which have not been taken into account, this indicates that low heights of burst do not affect crater parameters significantly.

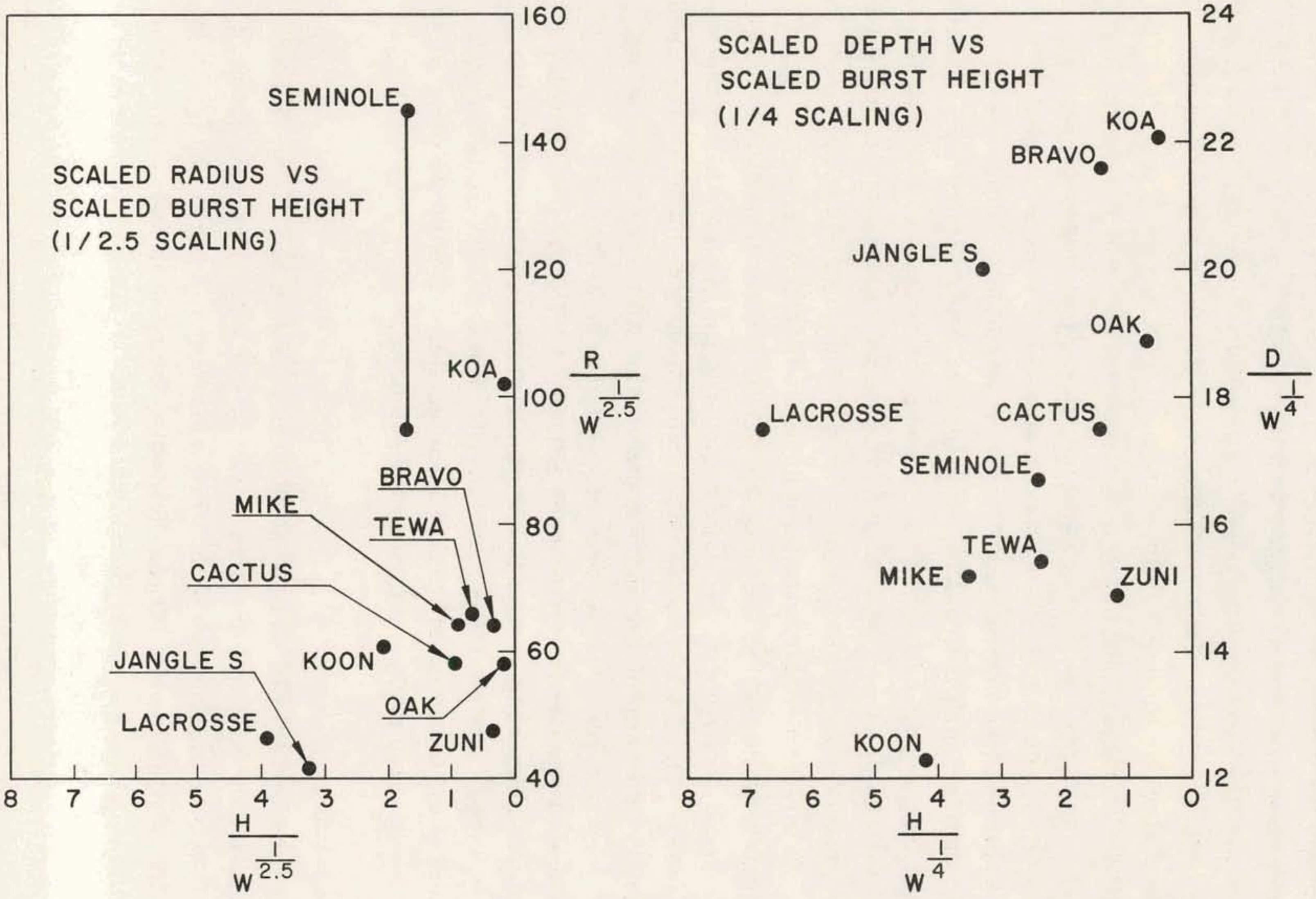

Fig. 43. Scaled crater parameters vs scaled burst height.

Comparison of Crater Surveys

The 1964 surveys are generally in agreement with previous surveys. There are, however, a few apparent discrepancies, such as rays 3 and 6 of Seminole (see Fig. 26). These have been discounted and were not used in the interpretation of the data. A general discussion of the changes occurring in these craters will be made in the following sections.

Mechanics of Crater Alteration

A crater shape can be altered in many ways. These include: (a) erosion, (b) crater slope failures, (c) settlement, and (d) silting up from an external source of material. Each of these phenomena are discussed below.

(a) Erosion may occur either by weathering or wave action on the lips or slopes of the crater. Cactus was the only crater which had sufficient material in the lips to allow significant erosional changes in the crater to occur.

(b) Slope failures may be caused by several factors. Initial unstable slopes will fail or gradually erode to a stable configuration. The material in the slopes, fractured and weakened by the detonation, will be less stable than in the preshot condition. Subsequent water action could eventually cause these slopes to fail. A nearby detonation could cause slope failures either by water-washing the crater or by the force of the ground shock on the crater slopes. However, ground shock did not appear to significantly alter the slopes of either Mike or Lacrosse craters as a result of the adjacent Koa and Cactus detonations, respectively.

(c) Settlement of suspended silt and sand in the crater from the detonation will gradually decrease the depth of the crater. This is evident in the Mike and Koa craters. The material is "trapped" in the crater and will eventually settle to the bottom. Settlement and consolidation of fallback material in a crater will increase the depth of the crater. However, this is not important in this study since an insignificant amount of fallback material is present in craters formed by surface detonations.

(d) An external source can be sand or finer material which is eroded and carried as suspended load or bed load by strong wave and water action. When the energy of the wave is dissipated, the load will settle out. Although there is not an abundant amount of transportable material present on atolls, a crater's geometry is such that much of the available material will be preferentially deposited at points in or around the crater.

Crater Changes

All of the craters have undergone a certain amount of erosion. For the most part this seems to be in the form of slope readjustment. Steeper slopes have eroded to more gentle slopes, with the eroded material being displaced to more stable positions further down the slope (see Fig. 19). The Cactus crater had sandy lips which were amenable to erosion by wave undercutting, causing a general filling in of the slopes in the crater (see Fig. 37). The Lacrosse crater had lips composed of beach rock, which are difficult to erode; therefore no significant alteration of these lips are apparent.

No major slope failures are in evidence except along ray 5 of the Seminole crater (see Fig. 26). As mentioned earlier, this was probably caused by the unstable condition of the medium. However, grading of the lip after the shot may have contributed to this. The extent that the Seminole lip was cut down and the subsequent disposition of the graded material is not known. The Mike and Koa craters (Figs. 7 and 32) have undergone minor slope failures, which were probably due, for the most part, to erosion.

A large amount of settlement of suspended material has occurred in the Mike and Koa craters. The great amount of material in suspension was apparent from the erroneous fathometer reading following the Koa detonation (see p. 50). Material in suspension was found in all the large craters. It is expected that the small craters would also exhibit this characteristic, although the effect is not apparent as in the large craters.

Material deposited from external sources is most evident in the Lacrosse and Cactus craters. This may be shown in Fig. 44, a 1964 aerial view of the Cactus and Lacrosse craters. The wave front is from the east (upper right), producing a source of sand from a long-shore current along Yvonne Island. The direction of littoral drift is easily seen by the pattern of sand on the reef. The lip of the Lacrosse crater dissipates wave energy and causes wave refraction, which also reduces wave energy. This reduction decreases the load-carrying capacity of the wave, resulting in sedimentation

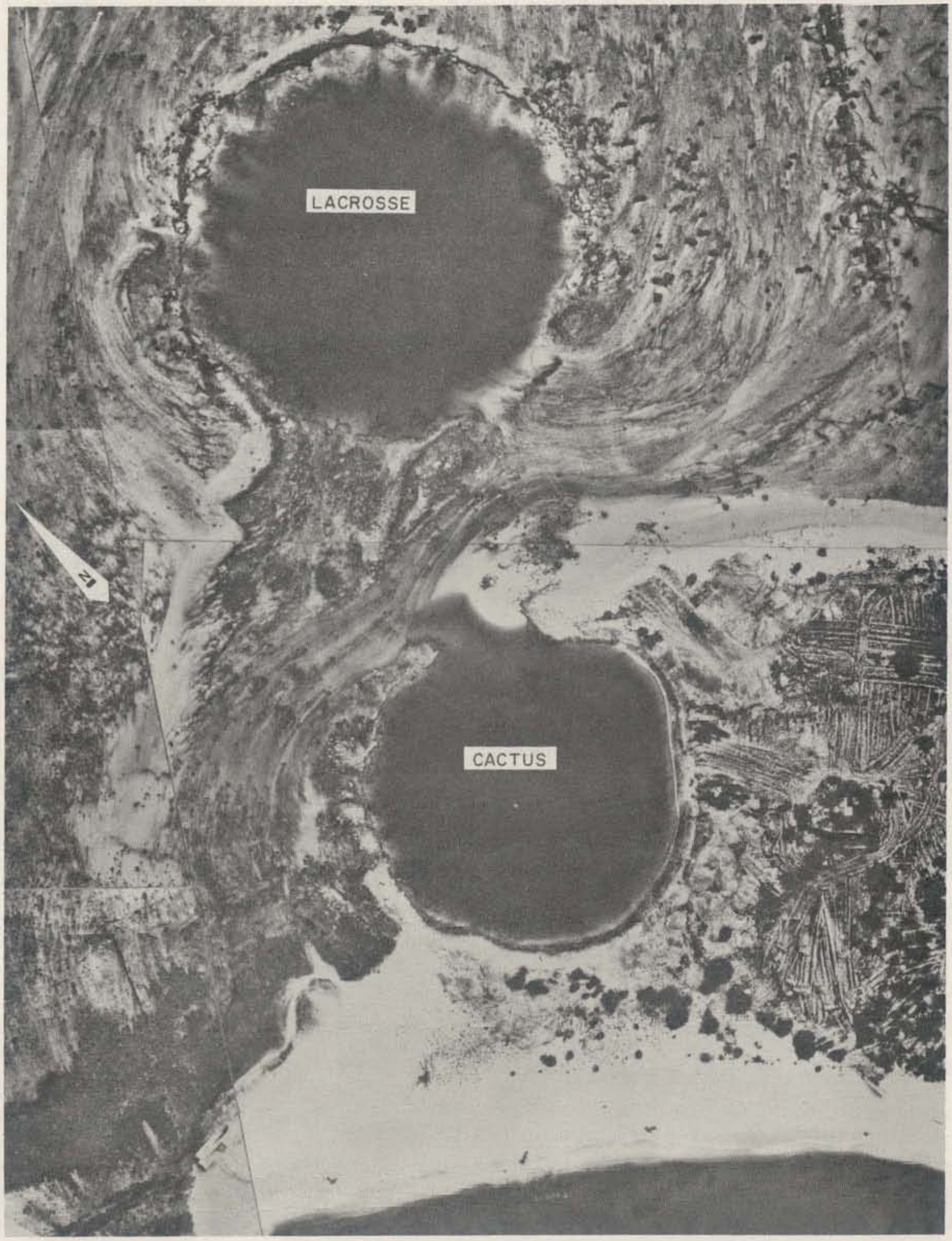

Fig. 44. 1964 aerial photomosaic of Lacrosse and Cactus craters.

as shown by the sand patterns around the crater. In places where the water overtops or penetrates the Lacrosse lip, the wave is refracted throughout the crater, resulting in sand deposition in the crater. This can be observed at several locations around the crater. This effect is also quite noticeable in the entrance channel at the north lip of the Cactus crater. A large deposit of bed-load material is slowly filling this portion of the crater.

Extending down from the west lip of the Lacrosse crater, a sand spit is forming. This is caused by the turbulence and subsequent energy dissipation of the refracted waves combining together from each side of the crater. As these waves combine and sweep across the reef, portions of the existing sand bar are slowly being pushed into the lagoon (lower left of photograph). If the Lacrosse crater had not been present, there is a good chance that the entrance channel of Cactus crater would have been eroded, similar to the Koon crater (see Fig. 14).

The Mike and Koa craters also seem to be receiving a certain amount of external debris. This may be observed in Fig. 45. Sand spits have built up between the sea and the craters. This material comes from debris from the sea and the reef. The transported material is most likely building up on ejecta blocks on the reef as a result of the detonations. This indicates that a significant amount of material is constantly being transported across the reef and into the craters.

The Seminole crater seems to be receiving its external source of material from erosion of its entrance channel to the reef (see Fig. 27). This is apparently due to diffraction of wave patterns around the island and into the inlet of the crater area. It is interesting to note the great amount of erosion occurring along the northern shore of Irene Island (Fig. 46). The previous geomorphic balance which originally formed the island has been altered by the changes which have taken place on the reef. This erosion is building up sand bars along the western tip of the island (Fig. 27).

Miscellaneous Effects

In addition to the investigations that were conducted pertinent to this study, several observations of related phenomena were observed which are worthy of mention.

Fig. 45. 1964 aerial photomosaic of Mike and Koa craters. Note the break in the reef opposite Mike crater. The Seminole crater is seen at top of photograph.

Fig. 46. 1964 photograph showing shore erosion at north end of Irene island. Note wave undercutting taking place.

1. During the 1964 survey, it was observed that a section of the seaward reef directly opposite the Mike crater was broken off (see Fig. 45). A close view of this break is shown in Fig. 47. Initially it was thought that this section had been spalled off as a result of the Mike detonation. However, postshot Mike photography and surveys (Figs. 5 and 6) indicate that the reef was still intact after the shot. Therefore it would appear that the Koa detonation may have directly affected the break. The reef was undoubtedly weakened and cracked as a result of the Mike shot. It is suggested that the Koa detonation further broke up this section and either spalled it off the reef completely, or that subsequent wave erosion caused or completed the break. Unfortunately, no information is available about the condition of the reef between post-Mike photography and the 1964 study.

2. The Koa ground zero was at the edge of the Mike crater. As a result the two craters coalesced (Fig. 45). The spacing between the two shot points was about 1.5 crater radii. The two craters form an almost linear channel with a small cusp between them. This cusp of hard material is in evidence along the surface (Fig. 45) and along the depth (Mike-Koa W. P. line in Fig. 7 and KR 1-4 line in Fig. 32) of the craters. The proximity of the Zuni crater to the Koon crater produced a similar effect (see Fig. 22). It is interesting to note that this effect would be expected from the simultaneous detonation of two explosives at optimum burial.

3. Several impact craters from the Koa detonation were observed on Irene Island and on the surrounding reef. One of the larger craters is shown by the depression north of the Seminole crater in Fig. 27. A close-up view of this crater is seen in Fig. 48, showing soil samples being taken from the lip. No ejecta blocks were found in the vicinity of these craters which could have produced them. It is probable that these were caused by large masses of weakly cemented coral which disintegrated on impact.

4. At the entrance channel to the Cactus crater an asymmetry is located which extends out into the reef (see Figs. 38 and 44). This elongation was present as a result of the detonation (see Fig. 33). It is believed that the medium in this region was within the rupture zone of the Lacrosse crater. The subsequent Cactus shot could have preferentially scoured away this already weakened material. However, a similar asymmetry is found at the entrance of the Seminole crater (see Figs. 25 and 28). This could have been caused by water-washing or subsequent wave erosion, which is not in evidence at the Cactus crater.

Fig. 47. Break in reef opposite the Mike crater (see Fig. 45).

Fig. 48. Impact crater on Irene Island from the Koa event. Seminole crater is seen in the background.

COMPARISON OF SURFACE SHOTS WITH UNDERGROUND SHOTS

The craters at the Pacific Proving Grounds have been very valuable in studying long-term changes associated with nuclear excavations. However, since Plowshare applications consider craters produced by nuclear explosives at optimum burial, the differences in craters formed by surface and sub-surface detonations should be noted. In this way, it will be possible to gain an insight into comparable engineering phenomena.

Cratering Mechanism

The major difference, of course, would be a much different crater. Assuming scaling factors from Sedan,[13] i.e.:

Depth of burst (DOB)	$= 163\ W^{1/3.4}$
Crater radius (R)	$= 155\ W^{1/3.4}$
Crater depth (D)	$= 82\ W^{1/3.4}$

and comparing these with scaling factors for the Pacific craters, i. e.:

Crater radius (R)	$= 50\ W^{1/2.5}$
Crater depth (D)	$= 18\ W^{1/4}$

several interesting results are observed as noted below.

Radius

Considering first the radius, it is seen that at low-yield detonations of the order of a few kilotons, an underground shot will produce a much larger crater. For example, if the Cactus shot was buried at optimum depth, the crater radius would have been almost twice as large (360 ft) as its present dimensions. However, since the yield dependence of the surface crater radius (1/2.5) is greater than that for buried explosives (1/3.4) there will be a critical yield beyond which surface detonations will produce a crater with a radius larger than the same yield buried at optimum. Thus, using Sedan parameters, a 10,400-kt detonation at optimum burial (2700 ft deep) would produce a crater radius of 2300 ft, compared to the present 2800-ft radius of the Mike crater.

This phenomenon may be explained by the fact that for surface detonations, the fireball and corresponding surface overpressures appear to play a dominant role in determining crater radii. In this case, the force of gravity is insignificant. In a buried detonation, while crater dimensions increase as $W^{1/3.4}$, the volume of material which the detonation must act on against gravity increases as $W^{3/3.4}$ and the distance it must move it increases as $W^{1/3.4}$. Thus, as energy yields increase, a larger proportion of their energy must be used in overcoming gravity forces. Therefore larger underground detonations become less efficient at producing craters than surface shots, which are relatively independent of the force of gravity.

Depth

The comparison of crater depth produces a more consistent picture. An explosion at optimum burial will always produce a deeper crater than a surface explosion. With an increase in yield, the crater depth of the buried shot will increase faster than a surface shot. For example, a buried Cactus shot would produce a crater five times deeper than at present, while a buried Mike shot would produce a crater eight times deeper. This does not take into account the effect of water-washing, however.

The above comparisons of crater radius and depth assume that the dry alluvium at the Nevada Test Site will behave similarly to the saturated hard coral of atolls. This is not a good assumption for quantitative comparisons. However, if 1/3.4 scaling is valid for buried detonations in atolls, which is a reasonable assumption, the relative effects would still be valid.

Rupture Zone

The rupture zone in a buried detonation would be much greater than a surface shot. This is evident because of the much greater percentage of explosive energy which is transmitted directly into the surrounding medium from a buried detonation. Surface spall and uplift of rupture zone material during the excavation will further disturb the medium. Therefore, it would be expected that the rupture zone from a buried detonation would consist of more fractured material, extending out for a greater distance than the rupture zone from a surface shot. Also, because of the deeper craters produced by buried shots, the slopes of the rupture zone would be much steeper. Thus, rupture zone slopes would tend to be less stable in a buried detonation than from a surface shot.

Fallback Material

A large amount of fallback material will be present in a crater from a buried shot, whereas an insignificant amount is returned to a surface crater. This material could have an effect on the depth of a crater. If water rushes into the true crater before or during the time that fallback material is returning to the crater, the effect of dynamic compaction of the fallback material will be impeded. The fallback material would then be saturated, unconsolidated, and unstable. This could greatly decrease the initial depth of the crater and subsequently result in large settlements over a period of several years.

Lip and Ejecta Material

Because of the greater disturbance and upheaval in the rupture zone, a buried nuclear detonation will result in much higher true lips. Similarly, because of the much greater volumes of material excavated, the ejecta lips will be much higher. Therefore, the crater will be surrounded with a considerable amount of material. Unless a crater is located in fairly deep water, it will not be greatly water-washed. However, if water-washing does occur, much of the ejecta material would be washed into the crater. This will fill the crater to a much greater extent than in a surface shot because of the greater amount of ejecta material available. The true lip would not be expected to undergo significant changes because of its structurally intact configuration.

It is interesting to note how water-washing could be used to advantage in the excavation of a harbor. If the Mike event was detonated at optimum burial, producing a crater size shown in Fig. 5, it would be surrounded on three sides by a lip over 300 ft high. The breach to the lagoon would be fractured rupture zone material. Water-washing would undoubtedly occur through this breach, scouring a much deeper channel through the fractured material, while the rest of the crater would be relatively unaffected. Thus, the water-washing effect would be expected to produce a deep-water channel into the nuclear harbor.

Erosion and Silting

A crater produced by a nuclear detonation at optimum burial in an atoll should not experience the amount of erosion or silting up that was observed in the Pacific craters because of the lip which would be present around the crater. Assuming that the lip would be well above the water level, the outside of the lip would act like a beach. Wave energy would be dissipated, and sand will be deposited on the outer lip of the crater. It is possible that wave action could gradually erode the ejecta material from the lip. However, the true lip should be relatively unaffected by wave action. As an example of this, the Lacrosse crater (Figs. 19 and 20) still has much of its true lip and ejecta in place, even after several years of overtopping wave action. Thus the crater lip should protect a crater from excessive wave, erosion, or silting action in a manner similar to riprap on large rock-fill break waters.

Erosion of sandy lip material inside the crater could gradually weaken the exposed slopes of the crater. This was evident around the Cactus crater (Fig. 36). This process would continue until a beach had built up to dissipate the erosional effects of tidal and wave action. However, with a deeper crater this action would be much more severe than is evident with Cactus, and steps might have to be taken to reduce this effect.

A separate problem becomes evident where no lip exists, such as at the entrance to a nuclear harbor. This could become a location for large deposition of material as seen at the entrance to the Cactus crater (Fig. 44). If the entrance is deep and the slope falls off steeply similar to the lagoon entrance to the Mike crater, no silting would be expected. Under less ideal conditions, the effect of tidal and wave action in and out of the crater through the channel could be sufficient to keep the channel clear. Otherwise, an artificial jetty would have to be constructed out beyond the path of deposition to keep the channel clear. If a harbor must also be provided with a deep channel entrance excavated by nuclear explosives, the lip produced by the nuclear channel would provide an artificial jetty to the entrance and no silting would occur.

It is also of interest to note that, generally, most littoral drift seems to occur in shallow water depths (less than 6 ft), and is primarily deposited within 100 ft of the shoreline.[14] Thus, if a crater entrance is located beyond this distance, no significant deposition would be expected. In addition, a crater resulting from optimum burial would be much deeper than required for normal harbor operations; therefore, a minor amount of material deposition in a crater would not affect its usefulness.

It is obvious in this study that a nuclear crater could seriously alter the pattern of wave action, erosion, and deposition of material in the surrounding area. Therefore, it is necessary to study the anticipated effects of such a crater before one is excavated for civil applications.

SUMMARY

This study was conducted to observe the long-term effects of weathering on 10 nuclear craters over periods as long as 12 years. The study consisted of an investigation and resurvey of selected craters on Bikini and Eniwetok Atolls including documentary photography; hydrographic, topographic, and geologic data; and general engineering observations. These data were compared with information collected from previous pertinent reports and studies.

This report summarizes all the data from previous and present studies. Cratering curves for these surface detonations are developed, based on the empirical data. Changes in crater topography are noted and investigated. The alteration of shoreline processes as a result of nuclear craters is discussed. The comparison of craters formed by surface and subsurface detonations and subsequent phenomena is considered.

A separate report on the geological and engineering soils characteristics of the Eniwetok craters will be prepared by the Soils Division, U. S. Army Engineering Waterways Experiment Station.[4] This report will examine in more detail the formation and subsequent development of the nuclear crater profiles.

It is suggested that the present study form the basis for further investigations of the craters in the Pacific Proving Grounds. Future studies will provide additional information on the condition and changes occurring in the surrounding area.

CONCLUSIONS

The main conclusions to be drawn from this study are:

1. No major changes have occurred in the Eniwetok craters which were resurveyed, except for the large amount of material which filled the bottom of the Mike and Koa craters. Changes which were observed may be attributed to erosion, crater slope failures, settlement of material in suspension, or silting up from an external source. Some of the material in the bottom of the Mike crater was undoubtedly also deposited as a result of the backwash from the nearby Koa detonation.

2. Cratering curves developed from the craters under study indicate that for surface bursts, crater radius scales as $W^{1/2.5}$, similar to the growth of the fireball, while crater depth scales as $W^{1/4}$. The effect of the various heights of burst in these craters is relatively minor in determining crater dimensions.

3. A crater produced by a detonation at optimum burial will have a much different configuration from the craters in this study. Crater lips will be much higher; less water-washing will occur; crater slopes will be much steeper and less stable; the crater will be much better protected against external conditions.

4. A crater can radically affect the geomorphic features of the surrounding area. This should be an important consideration in the excavation of craters for civil applications.

ACKNOWLEDGMENTS

The authors wish to express appreciation to L. B. Ballou, Lawrence Radiation Laboratory; R. M. Mansfield, Project Engineer, and L. S. Hammond, Chief of Survey, Holmes and Narver, Inc. for their work in the planning and execution of the 1964 survey. T. J. Oliver, Lawrence Radiation Laboratory, provided excellent photographic coverage of the 1964 survey.

Thanks are also extended to W. C. Sherman and W. B. Steinriede, U. S. Army Engineer Waterways Experiment Station, for their assistance in the collection and interpretation of the geologic analyses made in this report.

The many agencies involved in the procurement of many figures and photographs in this report are thanked; in particular, the Livermore Branch, Field Command, Defense Atomic Support Agency.

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